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Lattice gauge theories with superconducting circuits

Enrique Rico Ortega

Friday, 14 June 2019

High-energy physics at ultra-cold temperatures

European Centre for Theoretical Studies in Nuclear Physics and Related Areas , Trento, Italy


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MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD
U.S. DEPARTMENT OF ENERGY
Office of Science
OpenSuperQ
QMiCS
QuroMorphic

The team

High-energy physics and lattice QCD:

D. Banerjee
M. Bögli
P. Stebler
P. Widmer
U.-J. Wiese

Bern

AMO and circuit-QED implementations:

G.K. Brennen, M. Dalmonte, I.L. Egusquiza, M. Hafezi, L. Lamata, D. Marcos, A. Mezzacapo, M. Müller, G. Pupillo, P. Rabl, C. Sabín, E. Solano, T.M. Stace, D. Vodola, P. Zoller

Bilbao, Innsbruck, Madrid, Maryland, New York, Nottingham, Queensland, Strasbourg, Sydney, Vienna

Classical simulations and tensor networks:

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S. Montangero
T. Pichler
P. Silvi
F. Tschirsich

Ulm

Related works: Lewenstein (Barcelona), Verstraete (Ghent-Vienna), Berges-Oberthaler (Heidelberg), Bañuls-Cirac-Jansen-Reznik (Munich-Tel Aviv-Zeuthen)

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Vision: simulation of “nuclear” physics and dense “quark” matter

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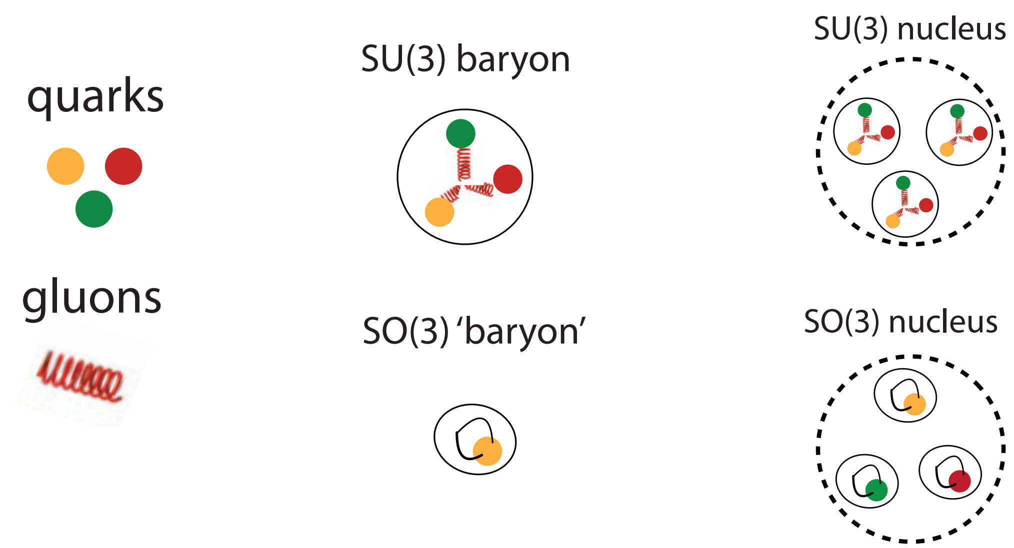
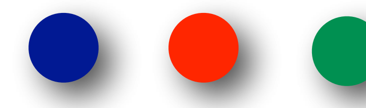
Vision: simulation of "nuclear" physics and dense "quark" matter

Goals: Development of quantum technologies toolbox for the implementation of systems with (non-)abelian gauge symmetry

Nuclear physics in a quantum simulator



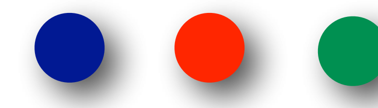
Quantum Chromodynamics: Confinement under normal conditions

Quarks and gluons carry a color charge $\hat{\psi}^{\alpha}_{\vec{r}}$ $\alpha =$ 

Quarks interact by exchanging gluons $\hat{\psi}^{\alpha\dagger}_{\vec{r}}\hat{U}^{\alpha\beta}_{\vec{r},\vec{r}+\check{\mu}}\hat{\psi}^{\beta}_{\vec{r}+\check{\mu}}$

Quantum Chromodynamics: Confinement under normal conditions

Quarks and gluons carry a color charge

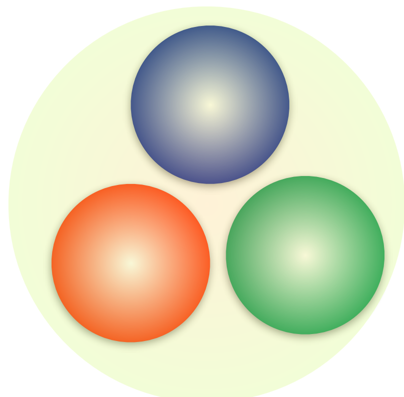
$\hat{\psi}^{\alpha}_{\vec{r}}$ $\alpha =$ 

Quarks interact by exchanging gluons

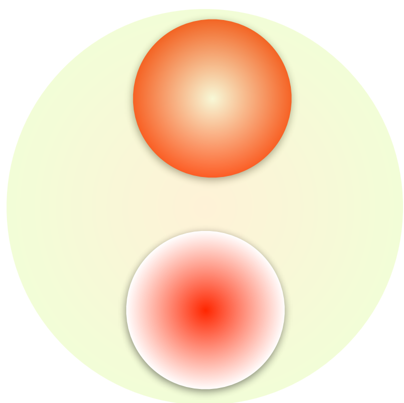
$$\hat{\psi}^{\alpha\dagger}_{\vec{r}}\hat{U}^{\alpha\beta}_{\vec{r},\vec{r}+\check{\mu}}\hat{\psi}^{\beta}_{\vec{r}+\check{\mu}}$$

Quarks are confined into color-neutral (color singlet) bound states (hadrons)

qqq baryons: proton, neutron, ...



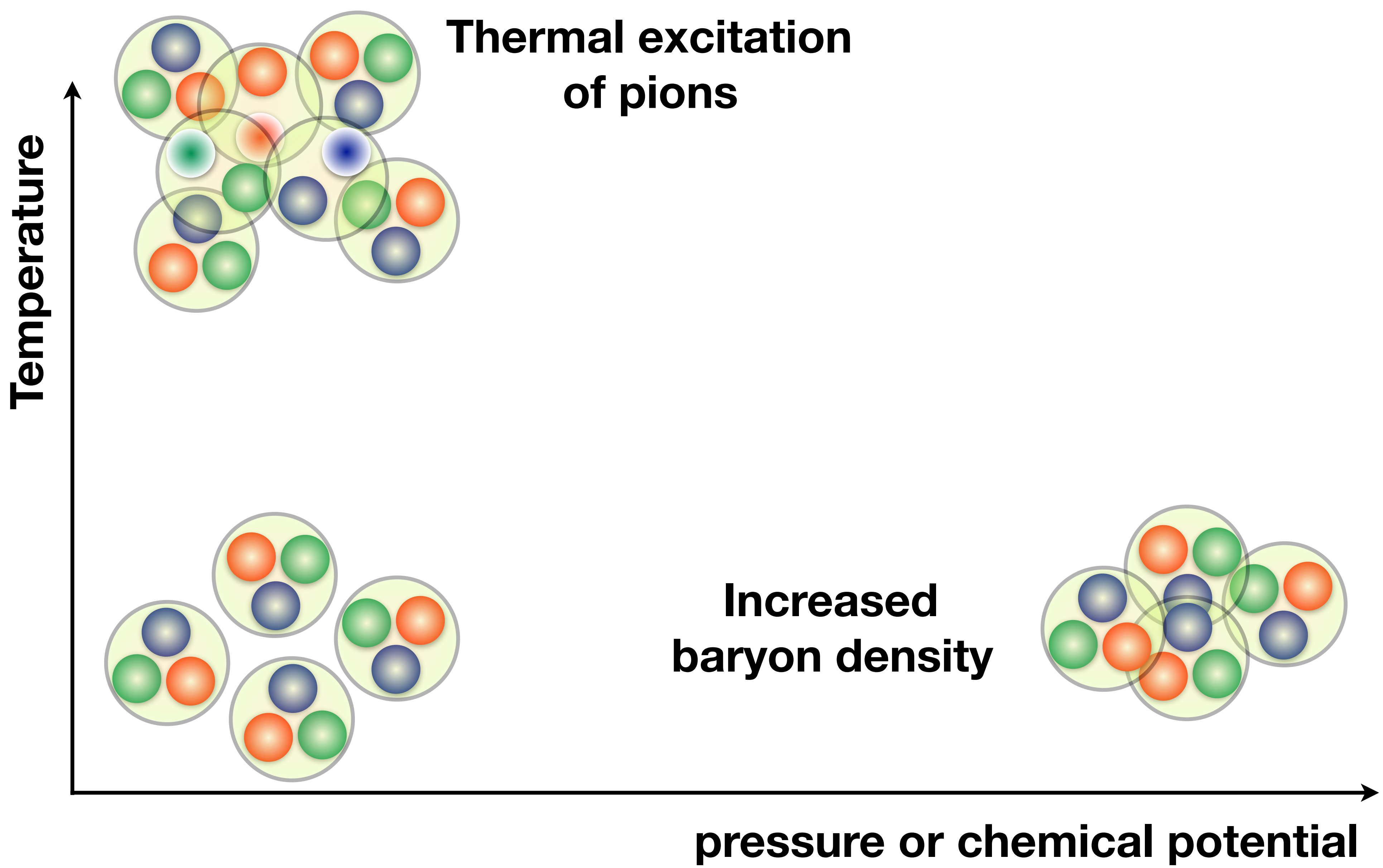
$\bar{q}q$ mesons: pions (lightest), kaon, rho, ...



QCD under extreme conditions

Compress or heat baryons → Hadrons overlap → Confinement is “lost”

Expect interesting/unusual behaviour



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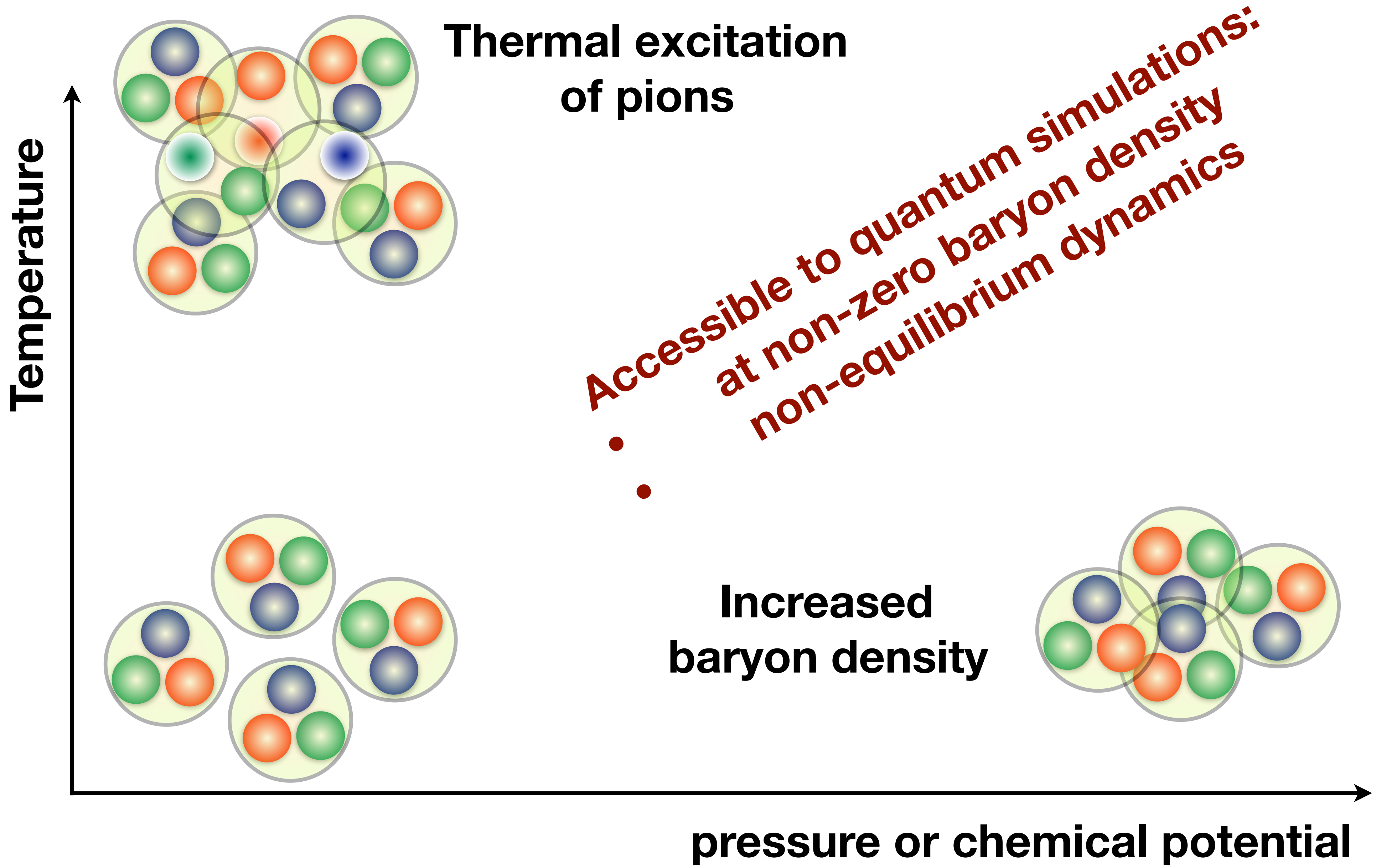


QCD under extreme conditions

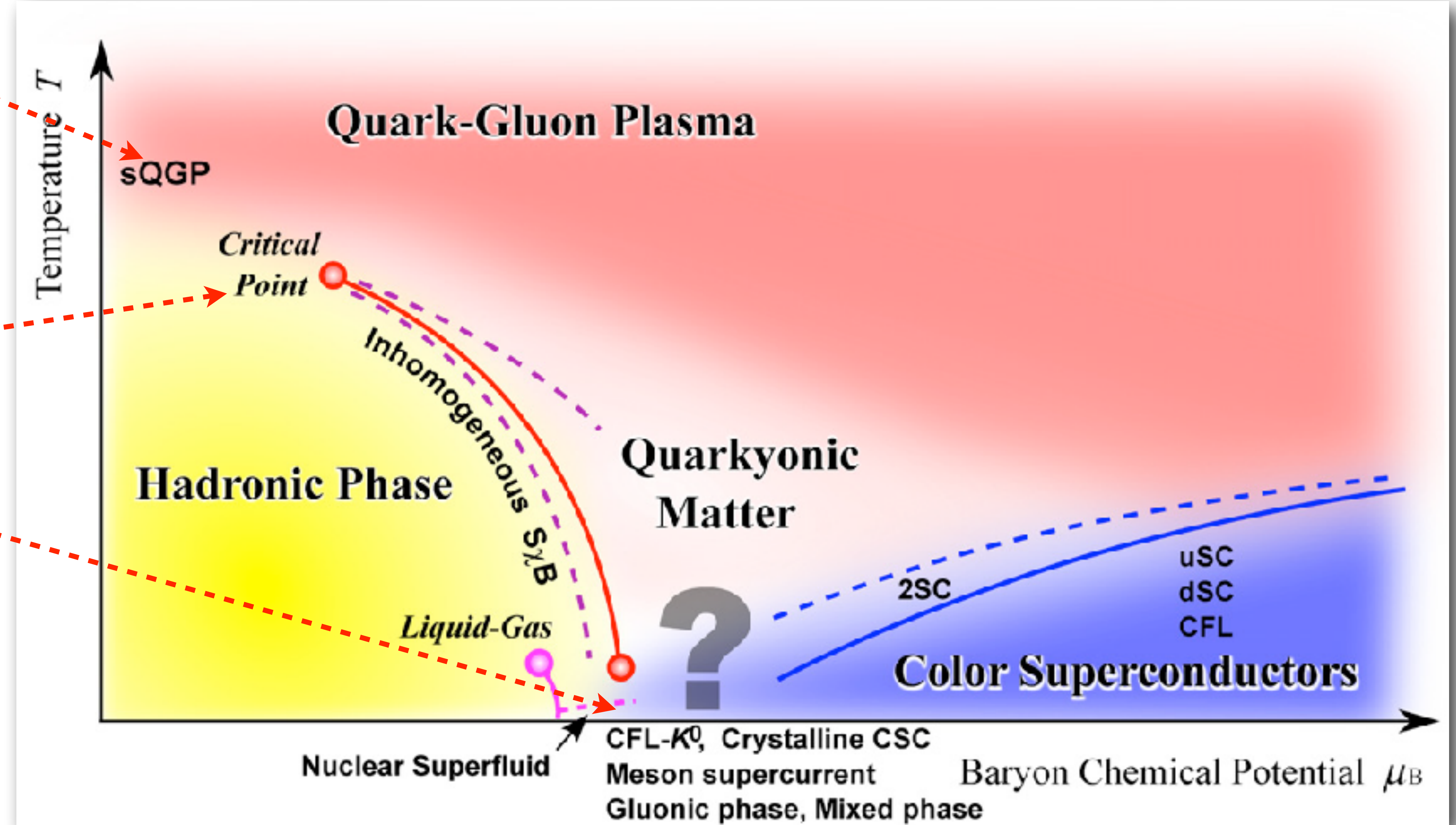
Compress or heat baryons → Hadrons overlap → Confinement is “lost”

A vast world to explore
QCD critical point: a challenge for experiment and theory

Early universe

Heavy-ion collisions

Neutron stars



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First experimental realisations in trapped ions platform

Quantum digital simulation

Real-time dynamics of lattice gauge theories with a few-qubit quantum computer

Esteban A. Martinez, Christine A. Muschik, Philipp Schindler, Daniel Nigg, Alexander Erhard, Markus Heyl, Philipp Hauke, Marcello Dalmonte, Thomas Monz, Peter Zoller & Rainer Blatt

Nature **534**, 516–519 (23 June 2016) | Download Citation

Hybrid (quantum-classical) approach

Self-verifying variational quantum simulation of lattice models

C. Kokail, C. Maier, R. van Bijnen, T. Brydges, M. K. Joshi, P. Jurcevic, C. A. Muschik, P. Silvi, R. Blatt, C. F. Roos & P. Zoller

Nature **569**, 355–360 (2019) | Download Citation

Quantum Technologies
for Lattice Gauge Theories

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Toolbox for Abelian lattice gauge theories with synthetic matter
O. Dutta, L. Tagliacozzo, M. Lewenstein, J. Zakrzewski
arXiv:1601.03303 (2016)

Lattice gauge theories simulations in the quantum information era
M. Dalmonte, S. Montangero
Contemporary Physics 57, 388 (2016)

Quantum Simulations of Lattice Gauge Theories using Ultracold Atoms in Optical Lattices
E. Zohar, J.I. Cirac, B. Reznik
Rep. Prog. Phys. 79, 014401 (2016)

Towards Quantum Simulating QCD
U.-J. Wiese
Nucl.Phys. A931, 246-256 (2014)

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Quantum Technologies for Lattice Gauge Theories

Volume 94B, number 2 PHYSICS LETTERS 28 July 1980

DYNAMICAL STABILITY OF LOCAL GAUGE SYMMETRY

Creation of Light From Chaos

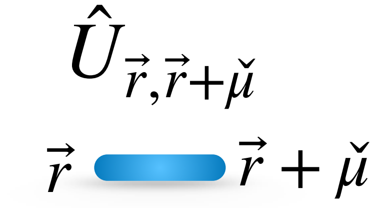
D. FOERSTER H.B. NIELSEN M. NINOMIYA

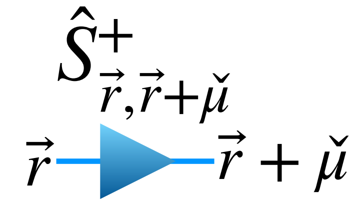
And God said "Let there be light", and there was light – Genesis 1–3

We show that the large distance behavior of gauge theories is stable, within certain limits, with respect to addition of gauge noninvariant interactions at small distances.

Content

- Quantum link formalism for gauge theories





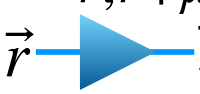
Content

- Quantum link formalism for gauge theories

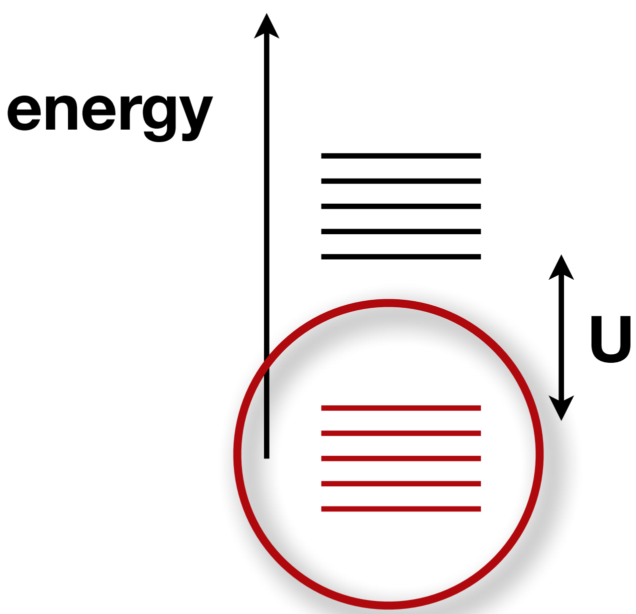
$\hat{U}_{\vec{r},\vec{r}+\check{\mu}}$

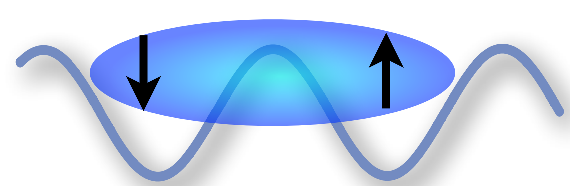
$\vec{r}$  $\vec{r}+\check{\mu}$

$\hat{S}^{+}_{\vec{r},\vec{r}+\check{\mu}}$

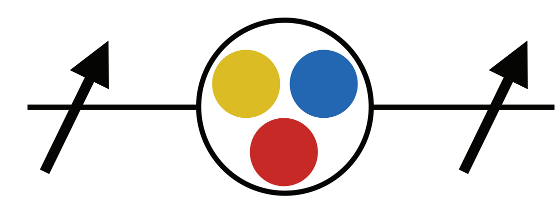
$\vec{r}$  $\vec{r}+\check{\mu}$

- Implementing the gauge invariance condition





color singlet hopping



encoding

Content

- Quantum link formalism for gauge theories

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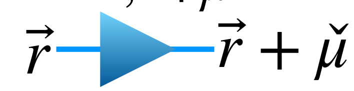
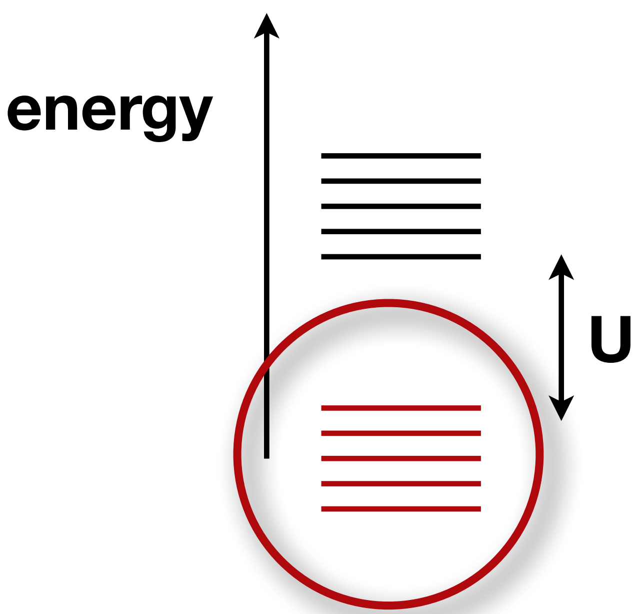
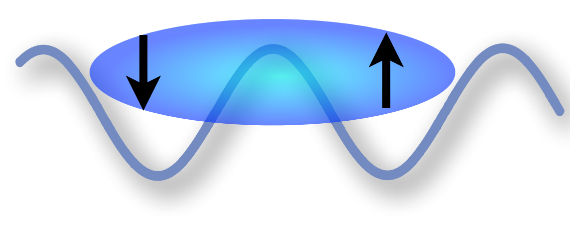


- Implementing the gauge invariance condition





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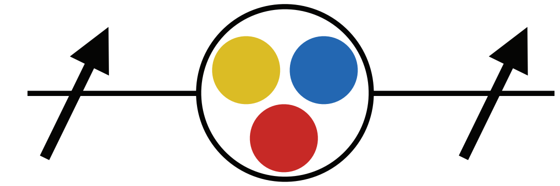
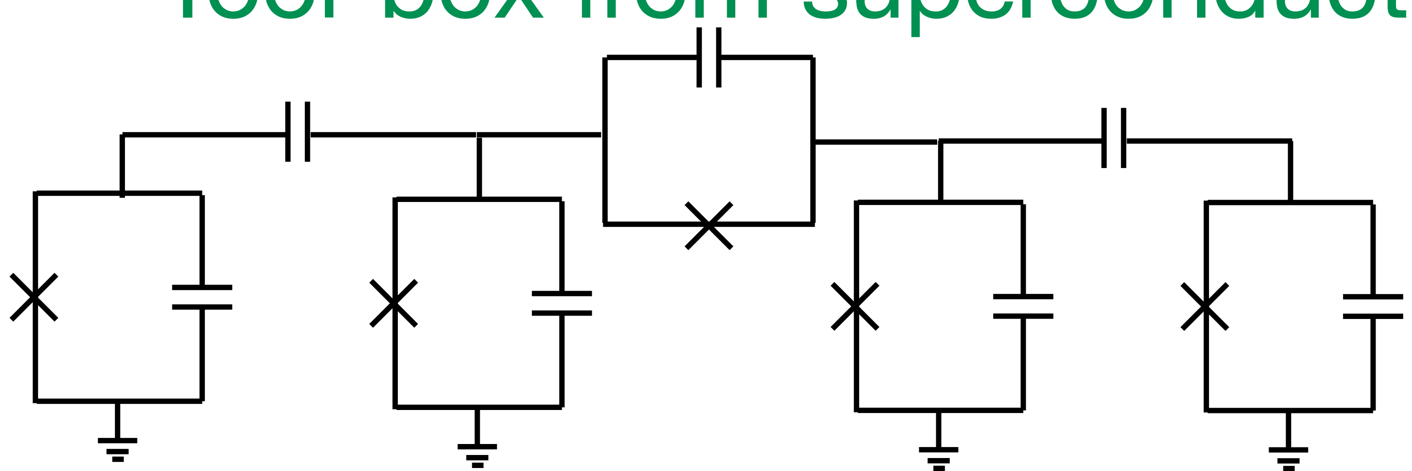
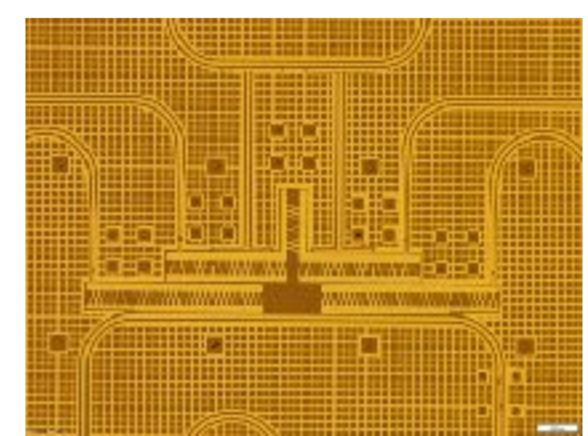


encoding

- Tool-box from superconducting circuits





Quantum link formalism

Gauge fields span a finite dimensional Hilbert space

Quantum link formalism

Gauge fields span a finite dimensional Hilbert space

U(1) quantum link model

Local degrees of freedom

Quantum link carries an electric flux in a finite-dimensional Hilbert space

Two conjugate variables

$$\hat{U}_{\vec{r},\vec{r}+\check{\mu}}$$

Gauge field

$$\hat{E}_{\vec{r},\vec{r}+\check{\mu}}$$

Electric field

$$[\hat{E}_{\vec{r},\vec{r}+\check{\mu}}, \hat{U}_{\vec{r},\vec{r}+\check{\mu}}] = \hat{U}_{\vec{r},\vec{r}+\check{\mu}}$$

$$\hat{U}_{\vec{r},\vec{r}+\check{\mu}}$$

$\vec{r}$ $\vec{r}+\check{\mu}$

Quantum link formalism

Gauge fields span a finite dimensional Hilbert space

U(1) quantum link model

Local degrees of freedom

Quantum link carries an electric flux in a finite-dimensional Hilbert space

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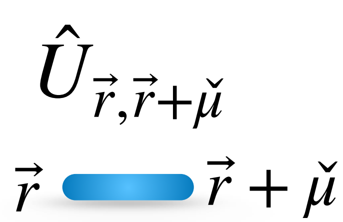
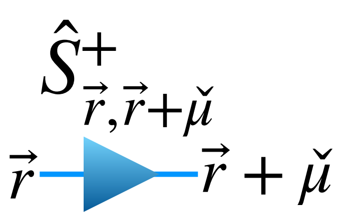
$$\hat{U}_{\vec{r},\vec{r}+\check{\mu}} \equiv \hat{S}^{+}_{\vec{r},\vec{r}+\check{\mu}} \qquad \hat{E}_{\vec{r},\vec{r}+\check{\mu}} \equiv \hat{S}^{(3)}_{\vec{r},\vec{r}+\check{\mu}}$$

Gauge field **Electric field**

$$[\hat{E}_{\vec{r},\vec{r}+\check{\mu}}, \hat{U}_{\vec{r},\vec{r}+\check{\mu}}] = \hat{U}_{\vec{r},\vec{r}+\check{\mu}} \qquad [\hat{S}^{(3)}_{\vec{r},\vec{r}+\check{\mu}}, \hat{S}^{+}_{\vec{r},\vec{r}+\check{\mu}}] = \hat{S}^{+}_{\vec{r},\vec{r}+\check{\mu}}$$

electric flux as a quantum spin





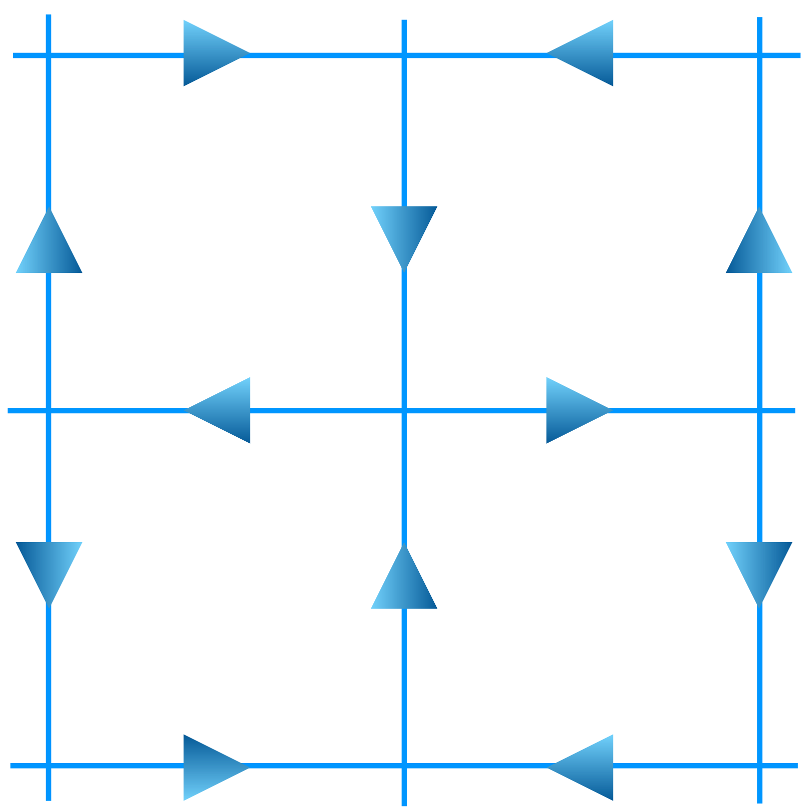
U(1) quantum link model

Local degrees of freedom

Electric flux as a quantum spin

$$\hat{U}_{\vec{r},\vec{r}+\check{\mu}} \equiv \hat{S}^{+}_{\vec{r},\vec{r}+\check{\mu}} \qquad \hat{E}_{\vec{r},\vec{r}+\check{\mu}} \equiv \hat{S}^{(3)}_{\vec{r},\vec{r}+\check{\mu}}$$

Gauge field **Electric field**



Electric field is the generator of gauge transformations

$$\hat{V}(\vec{r},\check{\mu}) = e^{\mathrm{i}\epsilon(\vec{r})\hat{E}_{\vec{r},\vec{r}+\check{\mu}}}$$

U(1) quantum link model

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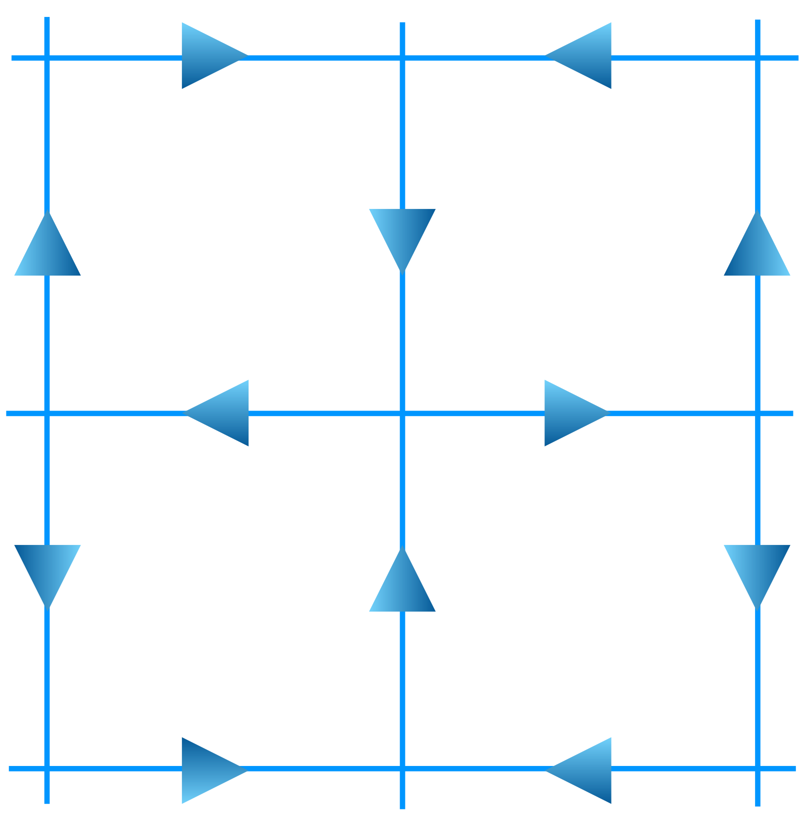
Local degrees of freedom and (first) Gauge constraint

Electric flux as a quantum spin

$$\hat{U}_{\vec{r},\vec{r}+\check{\mu}} \equiv \hat{S}^{+}_{\vec{r},\vec{r}+\check{\mu}} \qquad \hat{E}_{\vec{r},\vec{r}+\check{\mu}} \equiv \hat{S}^{(3)}_{\vec{r},\vec{r}+\check{\mu}}$$

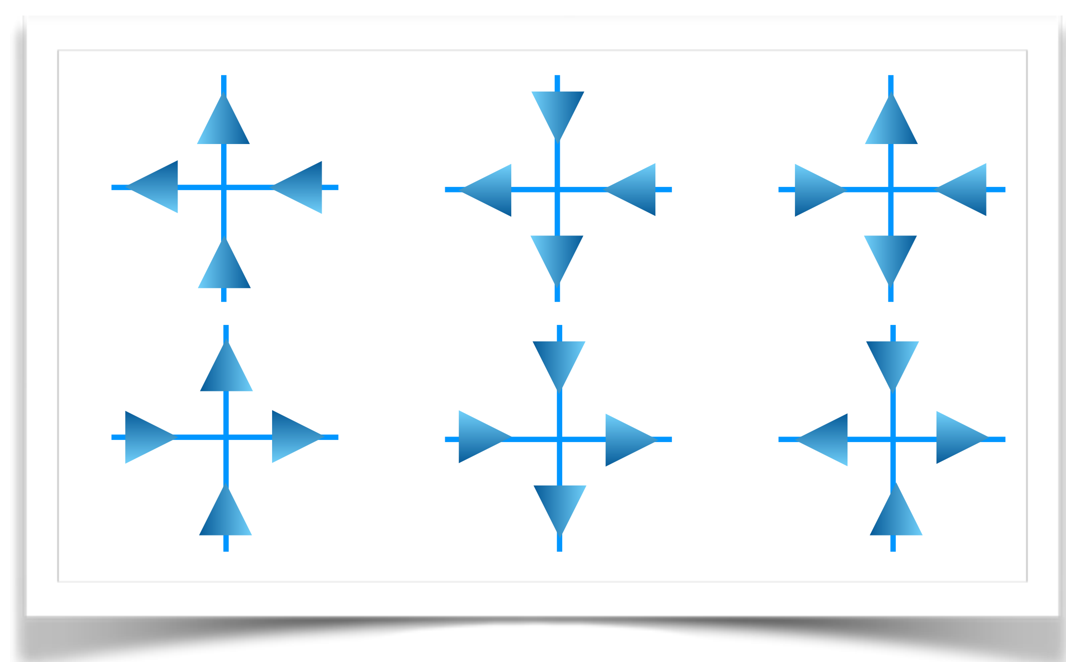
Gauge field **Electric field**



Electric field is the generator of gauge transformations

$$\hat{V}(\vec{r},\check{\mu}) = e^{\mathrm{i}\epsilon(\vec{r})\hat{E}_{\vec{r},\vec{r}+\check{\mu}}}$$

$$\prod_{\mu} \hat{V}(\vec{r},\check{\mu})\,|\,\textbf{phys}\rangle = |\,\textbf{phys}\rangle$$



Not all configuration are allowed
Zero net electric flux around every vertex
6-vertex model (2 in 2 out)

U(1) quantum link model

Schwinger representation

$\hat{U}_{\vec{r},\vec{r}+\check{\mu}}$

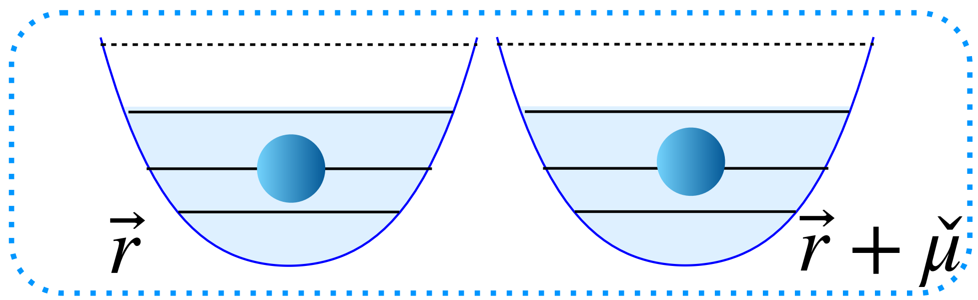
$\vec{r}$ $\vec{r}+\check{\mu}$

$\hat{S}^{+}_{\vec{r},\vec{r}+\check{\mu}}$

$\vec{r}$ $\vec{r}+\check{\mu}$

U(1) quantum link model

Schwinger representation



$$\hat{U}_{\vec{r},\vec{r}+\check{\mu}} \equiv \hat{S}^{+}_{\vec{r},\vec{r}+\check{\mu}} \equiv \hat{b}_{\vec{r},\check{\mu}}\hat{b}^{\dagger}_{\vec{r}+\check{\mu},-\check{\mu}}$$

Gauge field = "hopping"

$$\hat{E}_{\vec{r},\vec{r}+\check{\mu}} \equiv \hat{S}^{(3)}_{\vec{r},\vec{r}+\check{\mu}} \equiv \frac{\hat{n}_{\vec{r}+\check{\mu},-\check{\mu}} - \hat{n}_{\vec{r},\check{\mu}}}{2}$$

Electric field = occupation difference

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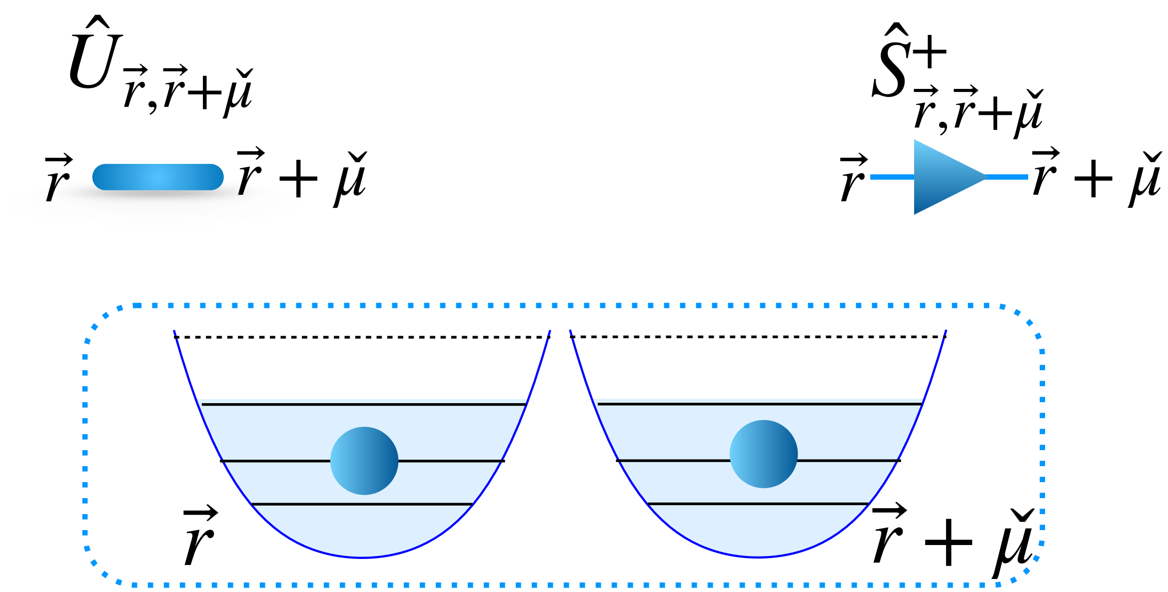
Schwinger representation



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Electric field = occupation difference

$$[\hat{b}_{\alpha},\hat{b}^{\dagger}_{\beta}]_{\pm} = \delta_{\alpha,\beta}$$

+fermion
-boson

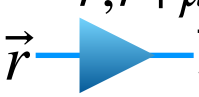
U(1) quantum link model

(second) Gauge constraint

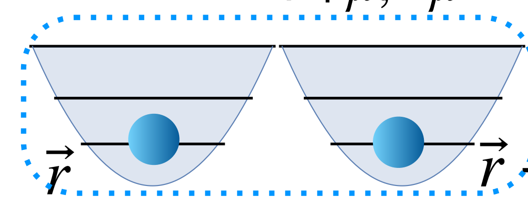
$\hat{U}_{\vec{r},\vec{r}+\check{\mu}}$

$\vec{r}$  $\vec{r}+\check{\mu}$

$\hat{S}^{+}_{\vec{r},\vec{r}+\check{\mu}}$

$\vec{r}$  $\vec{r}+\check{\mu}$

$\hat{b}_{\vec{r},\check{\mu}}\hat{b}^{\dagger}_{\vec{r}+\check{\mu},-\check{\mu}}$



2 Spin = occupation Number

$$S_{\vec{r},\vec{r}+\check{\mu}} \equiv \frac{\hat{n}_{\vec{r}+\check{\mu},-\check{\mu}} + \hat{n}_{\vec{r},\check{\mu}}}{2}$$

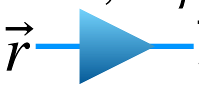
U(1) quantum link model

(second) Gauge constraint

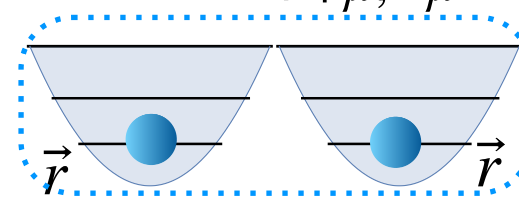
$\hat{U}_{\vec{r},\vec{r}+\check{\mu}}$

$\vec{r}$  $\vec{r}+\check{\mu}$

$\hat{S}^{+}_{\vec{r},\vec{r}+\check{\mu}}$

$\vec{r}$  $\vec{r}+\check{\mu}$

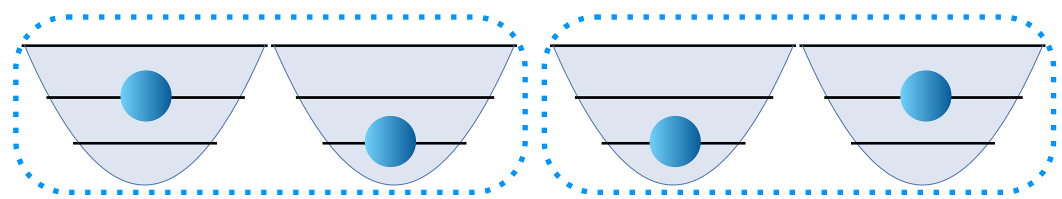
$\hat{b}_{\vec{r},\check{\mu}}\hat{b}^{\dagger}_{\vec{r}+\check{\mu},-\check{\mu}}$

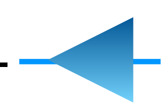


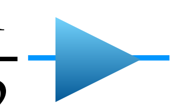
2 Spin = occupation Number

$$S_{\vec{r},\vec{r}+\check{\mu}} \equiv \frac{\hat{n}_{\vec{r}+\check{\mu},-\check{\mu}} + \hat{n}_{\vec{r},\check{\mu}}}{2}$$

spin-1/2



$E = -\frac{1}{2}$ 

$E = \frac{1}{2}$ 

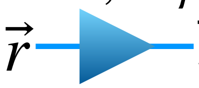
U(1) quantum link model

(second) Gauge constraint

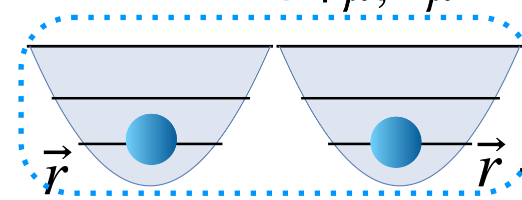
$\hat{U}_{\vec{r},\vec{r}+\check{\mu}}$

$\vec{r}$  $\vec{r}+\check{\mu}$

$\hat{S}^{+}_{\vec{r},\vec{r}+\check{\mu}}$

$\vec{r}$  $\vec{r}+\check{\mu}$

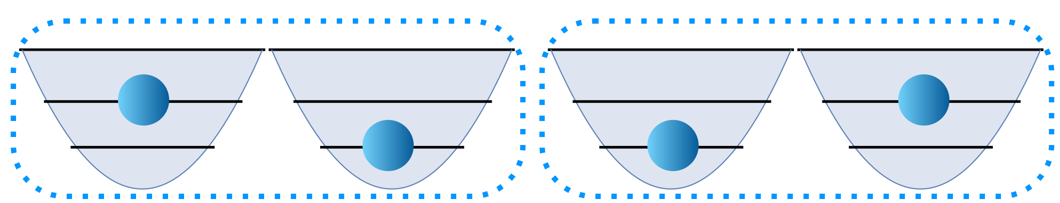
$\hat{b}_{\vec{r},\check{\mu}}\hat{b}^{\dagger}_{\vec{r}+\check{\mu},-\check{\mu}}$

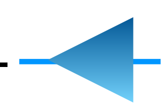
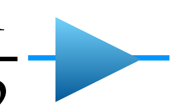


2 Spin = occupation Number

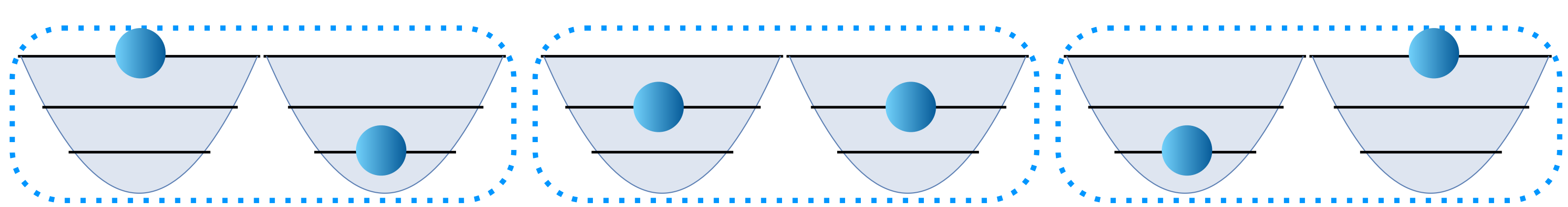
$$S_{\vec{r},\vec{r}+\check{\mu}} \equiv \frac{\hat{n}_{\vec{r}+\check{\mu},-\check{\mu}} + \hat{n}_{\vec{r},\check{\mu}}}{2}$$

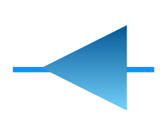
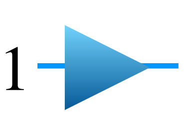
spin-1/2



$E = -\frac{1}{2}$  $E = \frac{1}{2}$ 

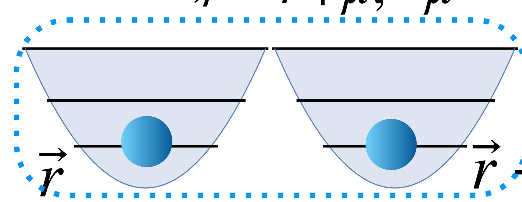
spin-1



$E = -1$  $E = 0$ $E = 1$ 

Non-abelian quantum link

Schwinger representation with internal indexes

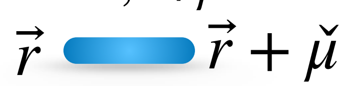


$$\alpha\beta = \begin{cases} 1 & : U(1) \\ \uparrow\downarrow & : U(2) \\ {\color{blue}b}{\color{red}r}{\color{green}g} & : U(3) \end{cases}$$

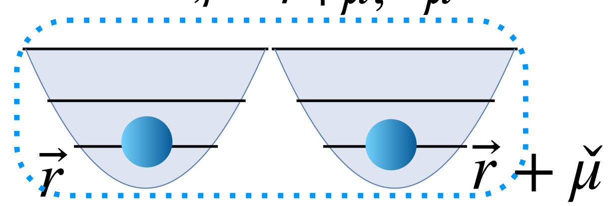
Non-abelian quantum link

Schwinger representation with internal indexes

$\hat{U}^{\alpha\beta}_{\vec{r},\vec{r}+\check{\mu}}$



$\hat{b}^{\alpha}_{\vec{r},\check{\mu}}\hat{b}^{\beta\dagger}_{\vec{r}+\check{\mu},-\check{\mu}}$



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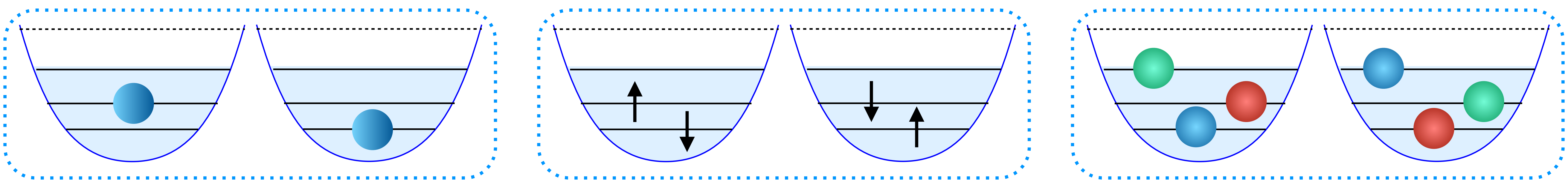


U(1) group **U(2) group** **U(3) group**

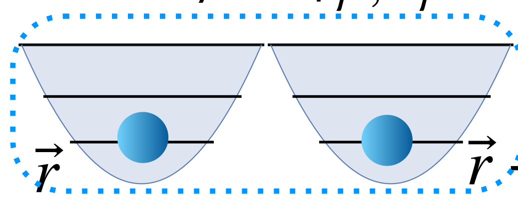
Non-abelian quantum link

Schwinger representation with internal indexes

$\hat{U}^{\alpha\beta}_{\vec{r},\vec{r}+\check{\mu}}$

$\vec{r}$  $\vec{r}+\check{\mu}$

$\hat{b}^{\alpha}_{\vec{r},\check{\mu}}\hat{b}^{\beta\dagger}_{\vec{r}+\check{\mu},-\check{\mu}}$



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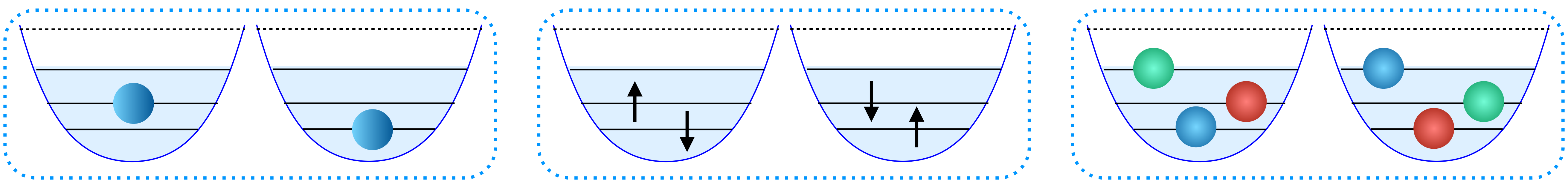


U(1) group **U(2) group** **U(3) group**

For orthogonal groups:

$$\hat{O}^{\alpha\beta}_{\vec{r},\vec{r}+\check{\mu}} = \hat{c}^{\alpha}_{\vec{r},\check{\mu}}\hat{c}^{\beta}_{\vec{r}+\check{\mu},-\check{\mu}}$$

$\vec{r}$  $\vec{r}+\check{\mu}$

$$\hat{c}^{\alpha}_{\vec{r},\check{\mu}} = \hat{c}^{\alpha\dagger}_{\vec{r},\check{\mu}}$$

from complex to real representations

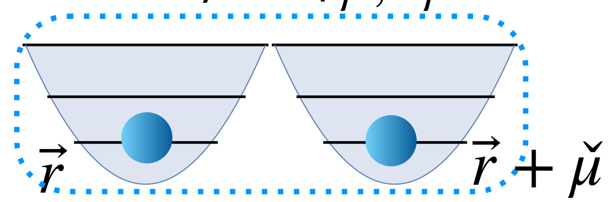
Non-abelian quantum link

Schwinger representation with internal indexes

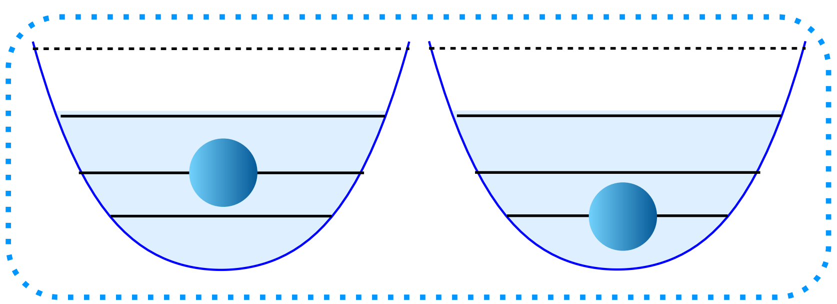
$$\hat{U}^{\alpha\beta}_{\vec{r},\vec{r}+\check{\mu}}$$

$\vec{r}$ $\vec{r}+\check{\mu}$

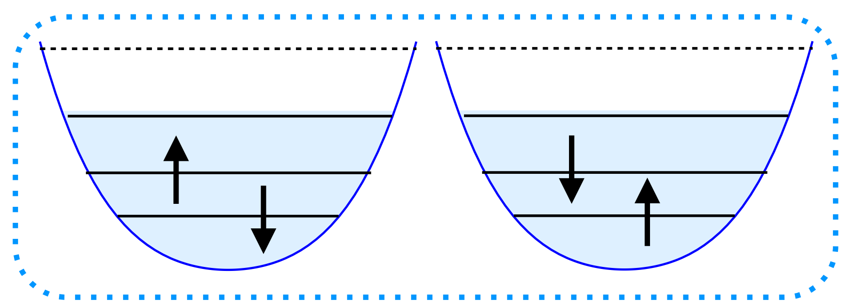
$$\hat{b}^{\alpha}_{\vec{r},\check{\mu}}\hat{b}^{\beta\dagger}_{\vec{r}+\check{\mu},-\check{\mu}}$$



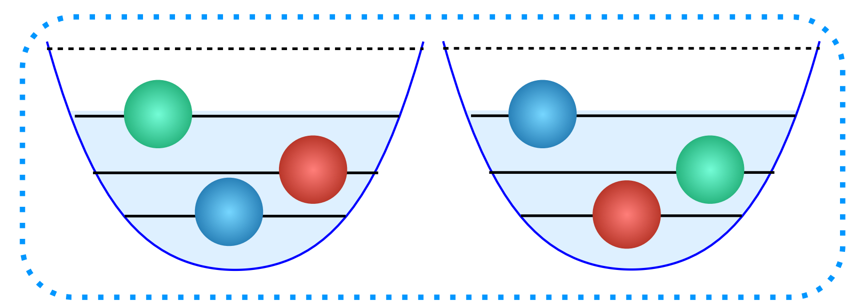
$$\alpha\beta = \begin{cases} 1 & : U(1) \\ \uparrow\downarrow & : U(2) \\ brg & : U(3) \end{cases}$$



U(1) group



U(2) group



U(3) group

For orthogonal groups:

$$\hat{O}^{\alpha\beta}_{\vec{r},\vec{r}+\check{\mu}} = \hat{c}^{\alpha}_{\vec{r},\check{\mu}}\hat{c}^{\beta}_{\vec{r}+\check{\mu},-\check{\mu}}$$

$\vec{r}$ $\vec{r}+\check{\mu}$

$$\hat{c}^{\alpha}_{\vec{r},\check{\mu}} = \hat{c}^{\alpha\dagger}_{\vec{r},\check{\mu}}$$

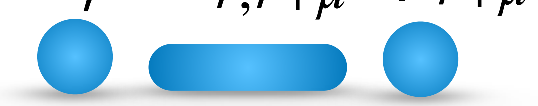
$$\hat{c}^{\alpha}_{\vec{r},\check{\mu}} = \hat{\sigma}^{\alpha}_{\vec{r},\check{\mu}}$$

O(3) group

from complex to real representations

U(1) quantum link model with matter field

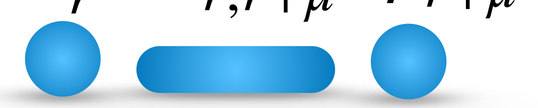
Gauge invariant quantum Hamiltonian



$$\hat{H} = \frac{g^2}{2}\sum_{\vec{r},\check{\mu}}[E_{\vec{r},\vec{r}+\check{\mu}}]^2 + \frac{1}{2}\sum_{\vec{r},\check{\mu}}\hat{\psi}^\dagger_{\vec{r}}\hat{U}_{\vec{r},\vec{r}+\check{\mu}}\hat{\psi}_{\vec{r}+\check{\mu}} + m\sum_{\vec{r}}(-1)^{\vec{r}}\hat{\psi}^\dagger_{\vec{r}}\hat{\psi}_{\vec{r}} + \mathrm{h.c.}$$

U(1) quantum link model with matter field

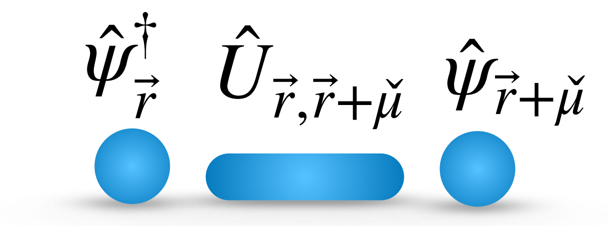
Gauge invariant quantum Hamiltonian



$$\hat{H} = \frac{g^2}{2}\sum_{\vec{r},\check{\mu}}[E_{\vec{r},\vec{r}+\check{\mu}}]^2 + \frac{1}{2}\sum_{\vec{r},\check{\mu}}\hat{\psi}^{\dagger}_{\vec{r}}\hat{U}_{\vec{r},\vec{r}+\check{\mu}}\hat{\psi}_{\vec{r}+\check{\mu}} + m\sum_{\vec{r}}(-1)^{\vec{r}}\hat{\psi}^{\dagger}_{\vec{r}}\hat{\psi}_{\vec{r}} + \mathrm{h.c.}$$

electric term (on-site interaction) | **matter-gauge interaction (…?…)** | **staggered mass (lattice potential)**

U(1) quantum link model with matter field



Local (gauge) symmetry

$$\hat{H} = \frac{g^2}{2} \sum_{\vec{r},\check{\mu}} [E_{\vec{r},\vec{r}+\check{\mu}}]^2 + \frac{1}{2} \sum_{\vec{r},\check{\mu}} \hat{\psi}^{\dagger}_{\vec{r}} \hat{U}_{\vec{r},\vec{r}+\check{\mu}} \hat{\psi}_{\vec{r}+\check{\mu}} + m \sum_{\vec{r}} (-1)^{\vec{r}} \hat{\psi}^{\dagger}_{\vec{r}} \hat{\psi}_{\vec{r}} + \mathrm{h.c.}$$

$$[\hat{H}, \hat{G}_{\vec{r}}] = 0 \ \forall \vec{r}$$

$$\hat{G}_{\vec{r}} = \hat{\psi}^{\dagger}_{\vec{r}} \hat{\psi}_{\vec{r}} - \sum_{\check{\mu}} \left(\hat{E}_{\vec{r},\vec{r}+\check{\mu}} - \hat{E}_{\vec{r}-\check{\mu},\vec{r}} \right)$$

gauge generator

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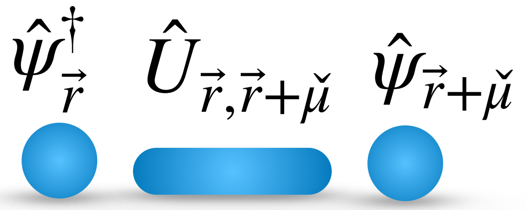
U(1) quantum link model with matter field



Local (gauge) symmetry

$$\hat{H} = \frac{g^2}{2}\sum_{\vec{r},\check{\mu}}[E_{\vec{r},\vec{r}+\check{\mu}}]^2 + \frac{1}{2}\sum_{\vec{r},\check{\mu}}\hat{\psi}^{\dagger}_{\vec{r}}\hat{U}_{\vec{r},\vec{r}+\check{\mu}}\hat{\psi}_{\vec{r}+\check{\mu}} + m\sum_{\vec{r}}(-1)^{\vec{r}}\hat{\psi}^{\dagger}_{\vec{r}}\hat{\psi}_{\vec{r}} + \mathrm{h.c.}$$

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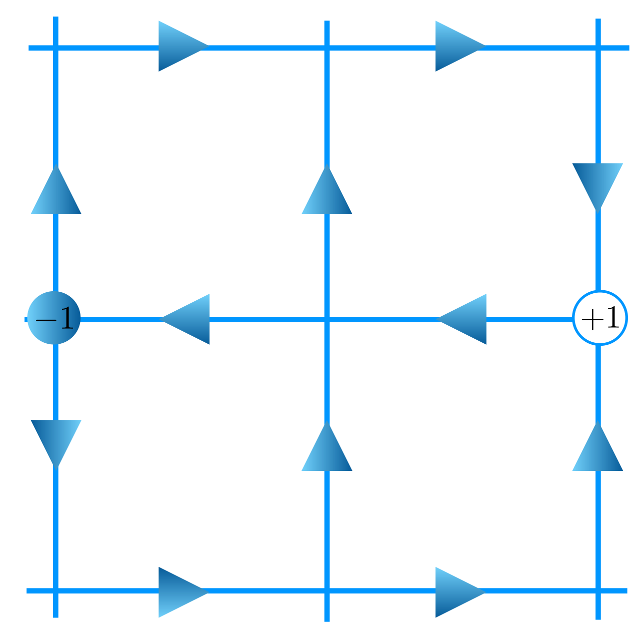
gauge generator

physical Hilbert space $\hat{G}_{\vec{r}}|\text{phys}\rangle = 0 \ \forall \vec{r}$

in the continuum $\hat{\rho} = \vec{\nabla}\cdot\hat{\vec{E}}$



charge is the source of electric field

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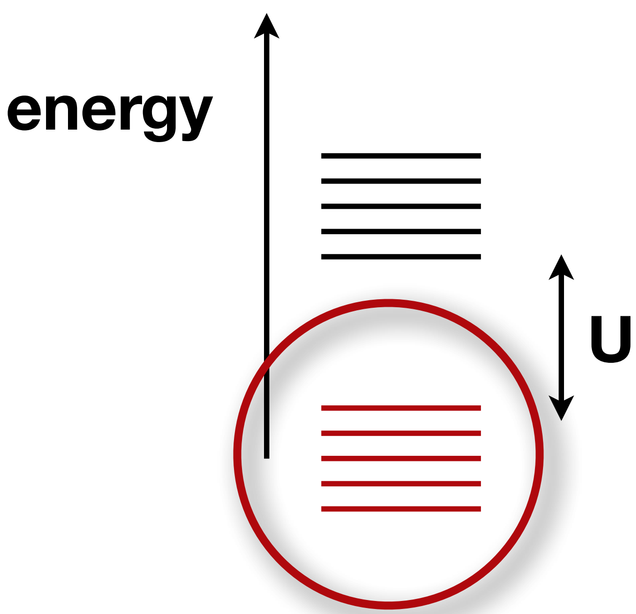
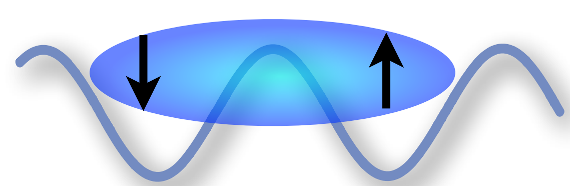
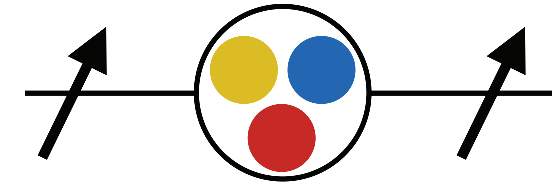
- Implementing the gauge invariance condition





color singlet
hopping



encoding

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PRL **109,** 175302 (2012) PHYSICAL REVIEW LETTERS week ending 26 OCTOBER 2012

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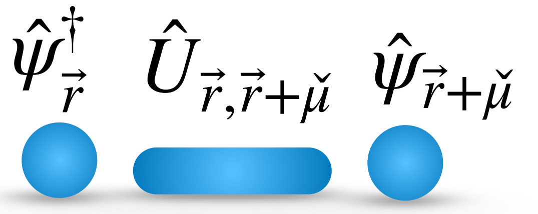
Atomic Quantum Simulation of Dynamical Gauge Fields Coupled to Fermionic Matter: From String Breaking to Evolution after a Quench

D. Banerjee,[1] M. Dalmonte,[2,3] M. Müller,[4] E. Rico,[2,3] P. Stebler,[1] U.-J. Wiese,[1] and P. Zoller[2,3,5]



$$\hat{H} = \frac{1}{2}\sum_{\vec{r},\check{\mu}} \hat{\psi}^{\dagger}_{\vec{r}} \hat{U}_{\vec{r},\vec{r}+\check{\mu}} \hat{\psi}_{\vec{r}+\check{\mu}} + \mathrm{h.c.} = \frac{1}{2}\sum_{\vec{\mathrm{r}},\check{\mu}} \hat{\psi}^{\dagger}_{\vec{\mathrm{r}}} \hat{\mathrm{b}}_{\vec{\mathrm{r}},\check{\mu}} \hat{\mathrm{b}}^{\dagger}_{\vec{\mathrm{r}}+\check{\mu},-\check{\mu}} \hat{\psi}_{\vec{\mathrm{r}}+\check{\mu}} + \mathrm{h.c.}$$

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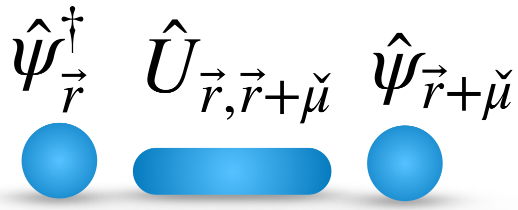
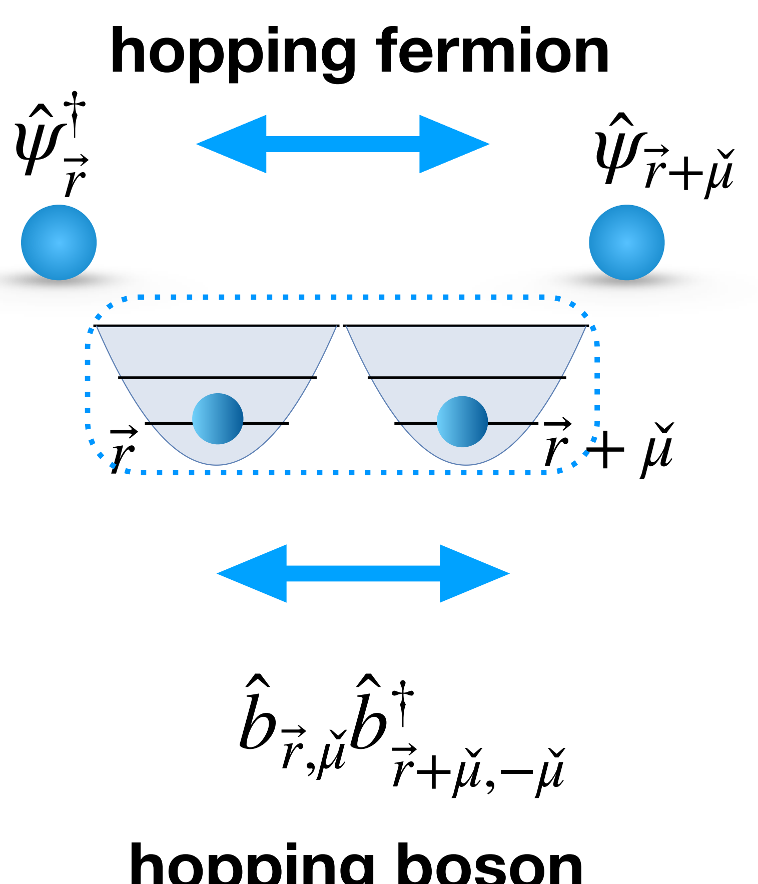


$$\hat{H} = \frac{1}{2}\sum_{\vec{r},\check{\mu}} \hat{\psi}^{\dagger}_{\vec{r}}\hat{U}_{\vec{r},\vec{r}+\check{\mu}}\hat{\psi}_{\vec{r}+\check{\mu}} + \mathrm{h.c.} = \frac{1}{2}\sum_{\vec{r},\check{\mu}} \hat{\psi}^{\dagger}_{\vec{r}}\hat{b}_{\vec{r},\check{\mu}}\hat{b}^{\dagger}_{\vec{r}+\check{\mu},-\check{\mu}}\hat{\psi}_{\vec{r}+\check{\mu}} + \mathrm{h.c.}$$

$$\hat{H}_{\mathrm{micro}} = J_F\sum_{\vec{r}} \hat{\psi}^{\dagger}_{\vec{r}}\hat{\psi}_{\vec{r}+\check{\mu}} + J_B\sum_{\vec{r}} \hat{b}_{\vec{r},\check{\mu}}\hat{b}^{\dagger}_{\vec{r},\check{\mu}} + \mathrm{h.c.}$$



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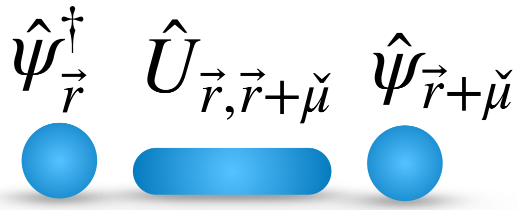

$$\hat{H} = \frac{1}{2}\sum_{\vec{r},\check{\mu}} \hat{\psi}^{\dagger}_{\vec{r}}\hat{U}_{\vec{r},\vec{r}+\check{\mu}}\hat{\psi}_{\vec{r}+\check{\mu}} + \mathrm{h.c.} = \frac{1}{2}\sum_{\vec{r},\check{\mu}} \hat{\psi}^{\dagger}_{\vec{r}}\hat{b}_{\vec{r},\check{\mu}}\hat{b}^{\dagger}_{\vec{r}+\check{\mu},-\check{\mu}}\hat{\psi}_{\vec{r}+\check{\mu}} + \mathrm{h.c.}$$

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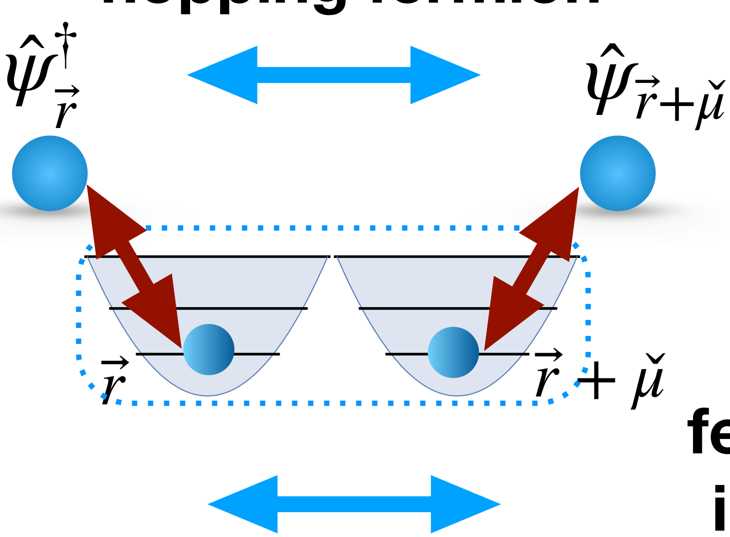
$$+U\sum_{\vec{r}}\left(\hat{G}_{\vec{r}}\right)^2$$

Fermi-Boson Hubbard model

hopping fermion



fermi-boson interaction

$\hat{b}_{\vec{r},\check{\mu}}\hat{b}^{\dagger}_{\vec{r}+\check{\mu},-\check{\mu}}$

hopping boson

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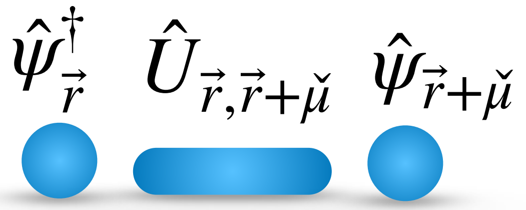

Emergent lattice gauge theory

$$\hat{H} = \frac{1}{2}\sum_{\vec{r},\check{\mu}} \hat{\psi}^\dagger_{\vec{r}}\hat{U}_{\vec{r},\vec{r}}\hat{\psi}_{\vec{r}+\check{\mu}} + \mathrm{h.c.} = \frac{1}{2}\sum_{\vec{r},\check{\mu}} \hat{\psi}^\dagger_{\vec{r}}\hat{b}_{\vec{r},\check{\mu}}\hat{b}^\dagger_{\vec{r}+\check{\mu},-\check{\mu}}\hat{\psi}_{\vec{r}+\check{\mu}} + \mathrm{h.c.}$$

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$$+U\sum_{\vec{r}}\left(\hat{G}_{\vec{r}}\right)^2$$

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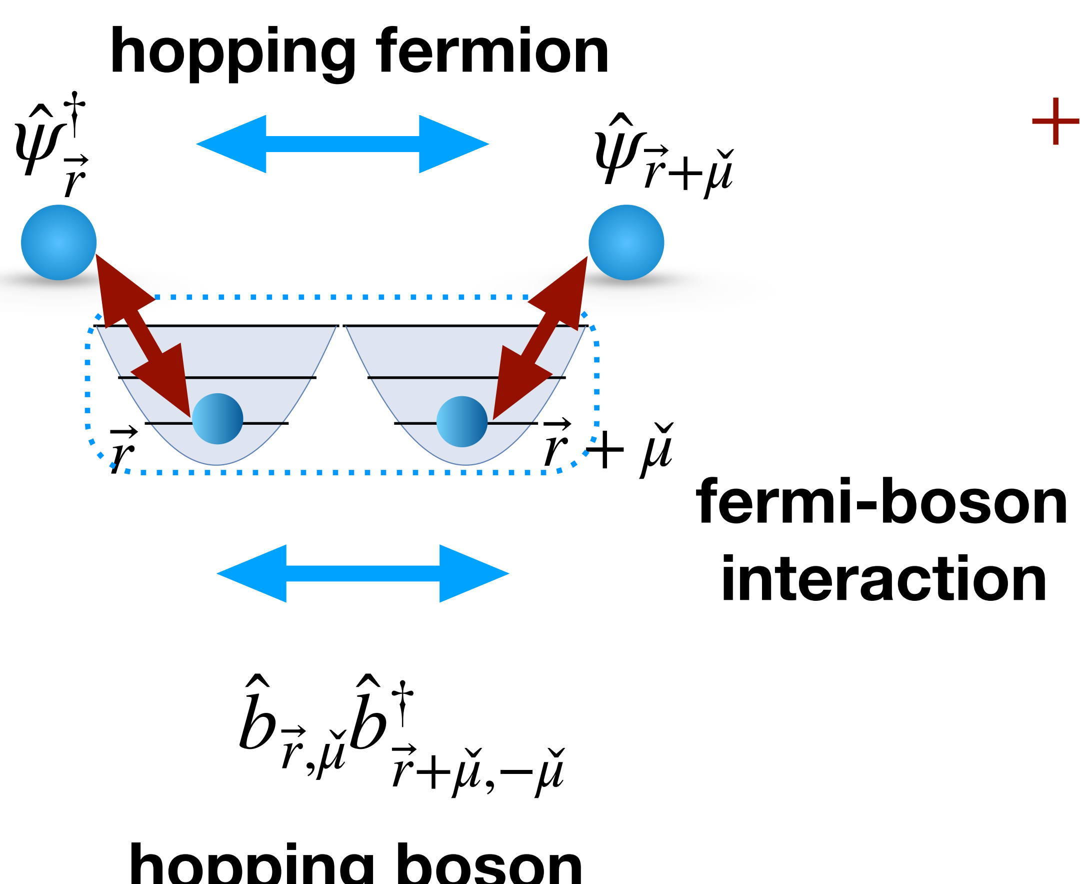

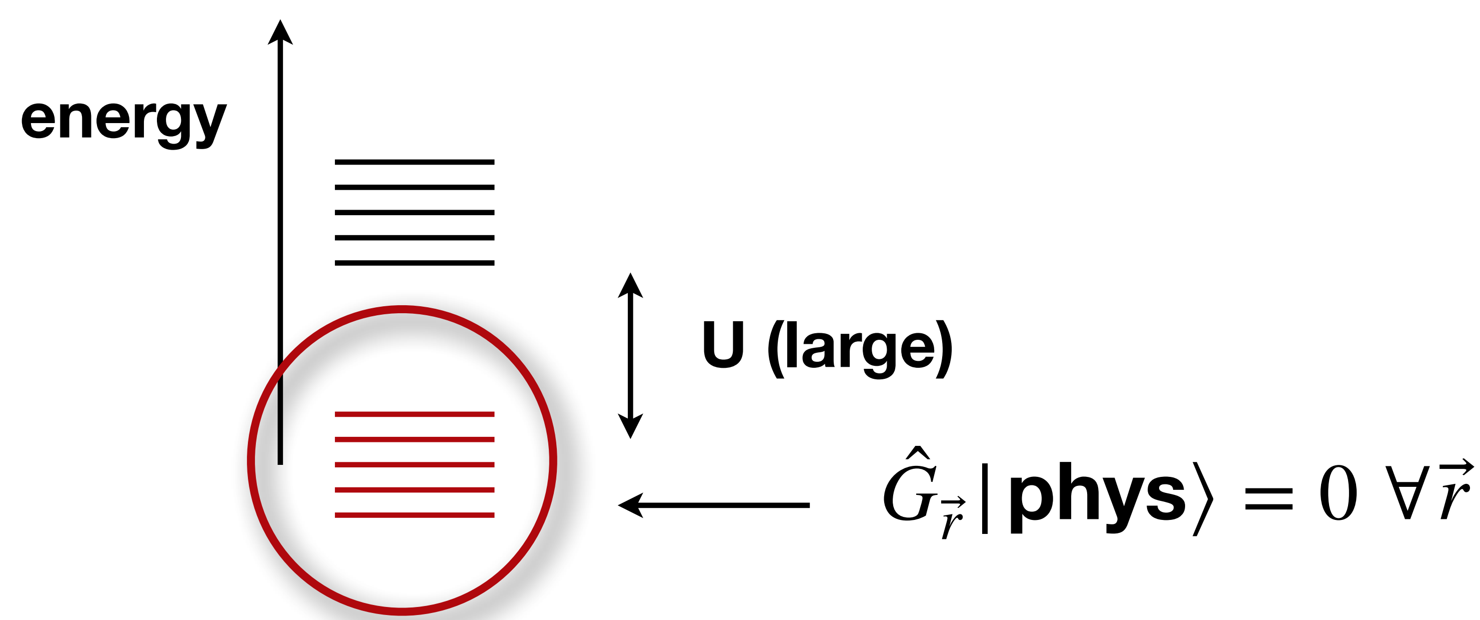

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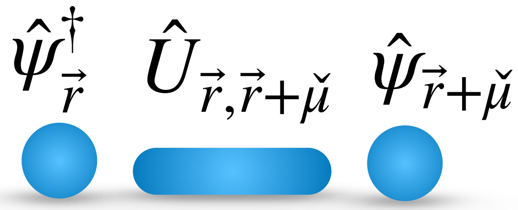

Emergent lattice gauge theory

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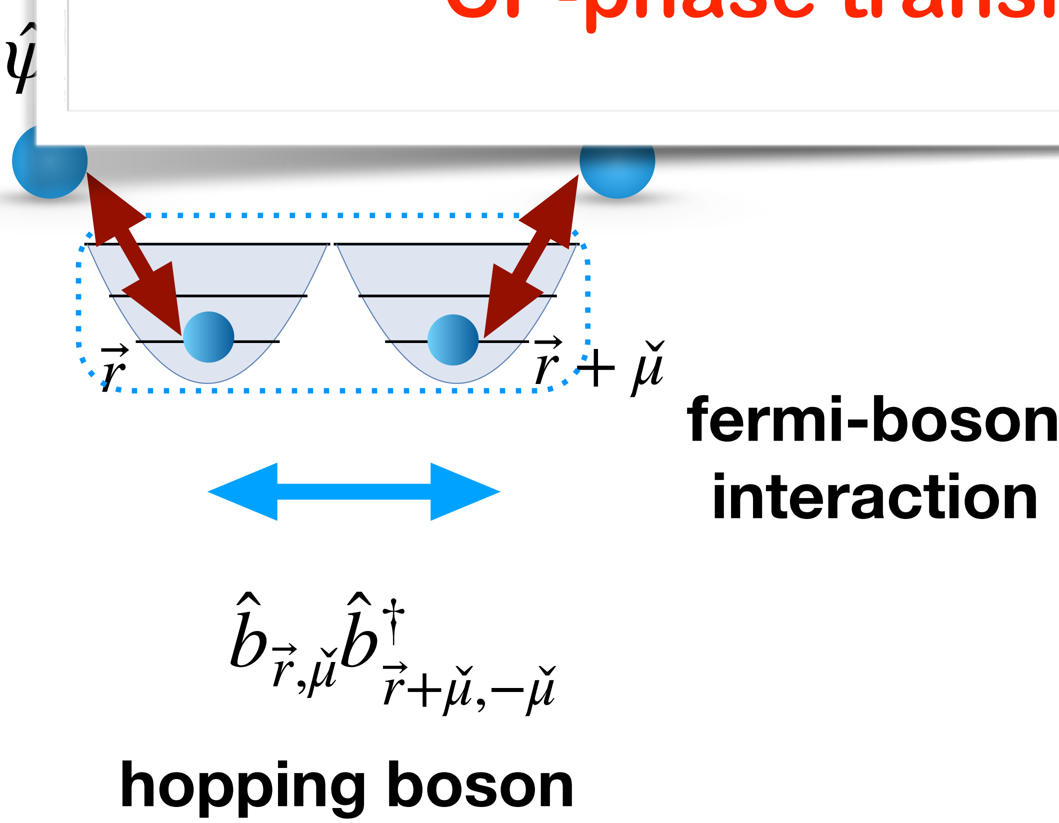
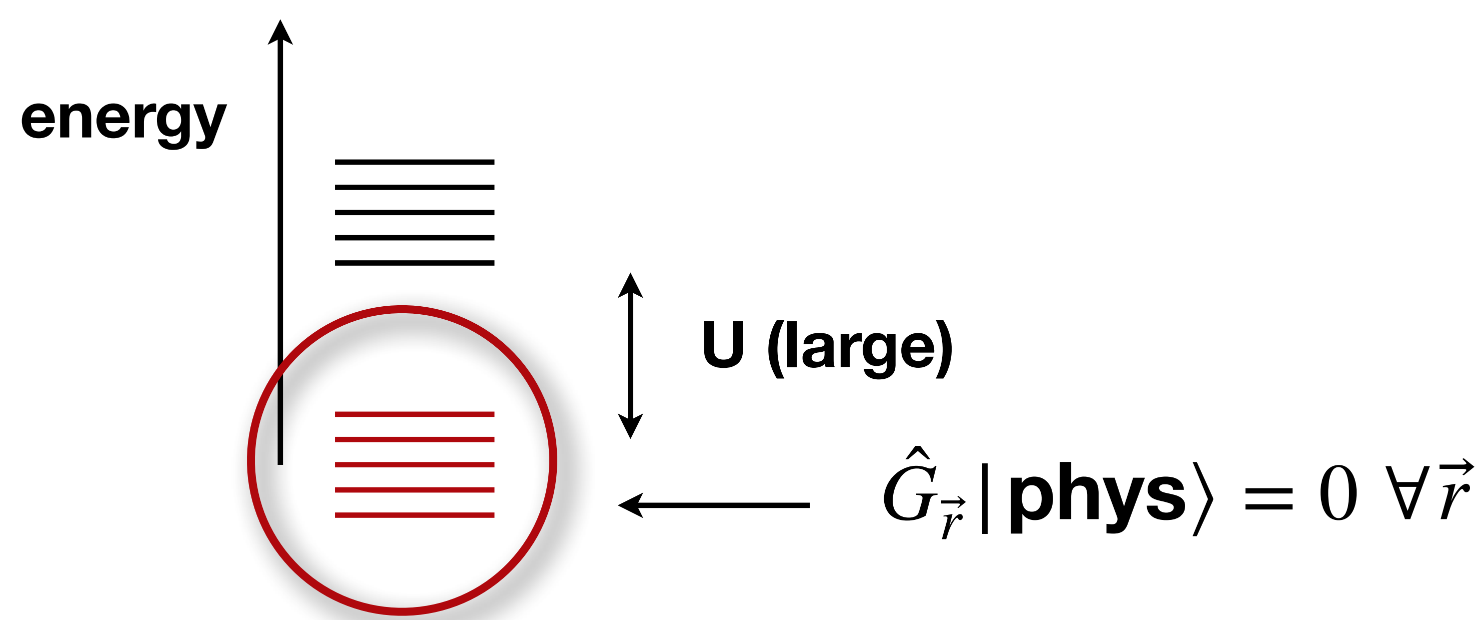
Features of the model:

Real time evolution of string breaking
CP-phase transition in QED in (1+1)-dimensions





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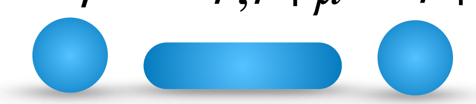
PRL 110, 125303 (2013) PHYSICAL REVIEW LETTERS week ending 22 MARCH 2013

Atomic Quantum Simulation of U(N) and SU(N) Non-Abelian Lattice Gauge Theories

D. Banerjee,[1] M. Bögli,[1] M. Dalmonte,[2] E. Rico,[2,3] P. Stebler,[1] U.-J. Wiese,[1] and P. Zoller[2,3]

$$\hat{\psi}^{\alpha\dagger}_{\vec{r}} \quad \hat{U}^{\alpha\beta}_{\vec{r},\vec{r}+\check{\mu}} \quad \hat{\psi}^{\beta}_{\vec{r}+\check{\mu}}$$



$$\hat{H} = \frac{1}{2}\sum_{\vec{r},\check{\mu}} \hat{\psi}^{\alpha\dagger}_{\vec{r}} \hat{U}^{\alpha\beta}_{\vec{r},\vec{r}+\check{\mu}} \hat{\psi}^{\beta}_{\vec{r}+\check{\mu}} + \mathrm{h.c.} = \frac{1}{2}\sum_{\vec{\mathrm{r}},\check{\mu}} (\hat{\psi}^{\alpha\dagger}_{\vec{\mathrm{r}}} \hat{\mathrm{b}}^{\alpha}_{\vec{\mathrm{r}},\check{\mu}})(\hat{\mathrm{b}}^{\beta\dagger}_{\vec{\mathrm{r}}+\check{\mu},-\check{\mu}} \hat{\psi}^{\beta}_{\vec{\mathrm{r}}+\check{\mu}}) + \mathrm{h.c.}$$

PRL 110, 125303 (2013) PHYSICAL REVIEW LETTERS week ending 22 MARCH 2013

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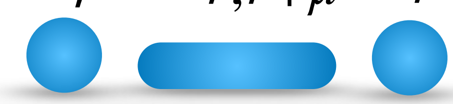
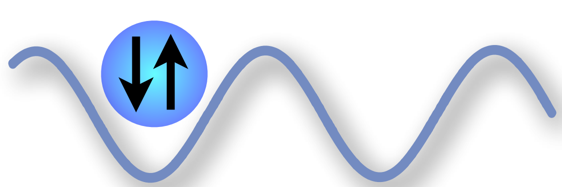
$$\hat{\psi}^{\alpha\dagger}_{\vec{r}} \; \hat{U}^{\alpha\beta}_{\vec{r},\vec{r}+\check{\mu}} \; \hat{\psi}^{\beta}_{\vec{r}+\check{\mu}}$$



$$\hat{H} = \frac{1}{2}\sum_{\vec{r},\check{\mu}} \hat{\psi}^{\alpha\dagger}_{\vec{r}} \hat{U}^{\alpha\beta}_{\vec{r},\vec{r}+\check{\mu}} \hat{\psi}^{\beta}_{\vec{r}+\check{\mu}} + \mathrm{h.c.} = \frac{1}{2}\sum_{\vec{\mathrm{r}},\check{\mu}} (\hat{\psi}^{\alpha\dagger}_{\vec{\mathrm{r}}} \hat{\mathrm{b}}^{\alpha}_{\vec{\mathrm{r}},\check{\mu}})(\hat{\mathrm{b}}^{\beta\dagger}_{\vec{\mathrm{r}}+\check{\mu},-\check{\mu}} \hat{\psi}^{\beta}_{\vec{\mathrm{r}}+\check{\mu}}) + \mathrm{h.c.}$$

$$\hat{H}_{\mathrm{micro}} = J \sum_{\vec{r},\check{\mu}} \hat{\psi}^{\alpha\dagger}_{\vec{r}} \hat{b}^{\alpha}_{\vec{r},\check{\mu}} + \mathrm{h.c.}$$



color singlet hopping

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PRL 110, 125303 (2013) PHYSICAL REVIEW LETTERS week ending 22 MARCH 2013

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Atomic Quantum Simulation of U(N) and SU(N) Non-Abelian Lattice Gauge Theories

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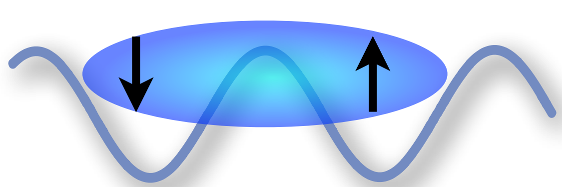

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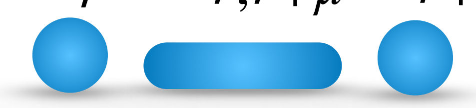

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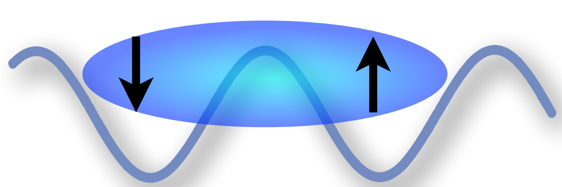
$$+U\sum_{\vec{r},\check{\mu}} \hat{N}^{2}_{\vec{r},\check{\mu}}$$



color singlet hopping

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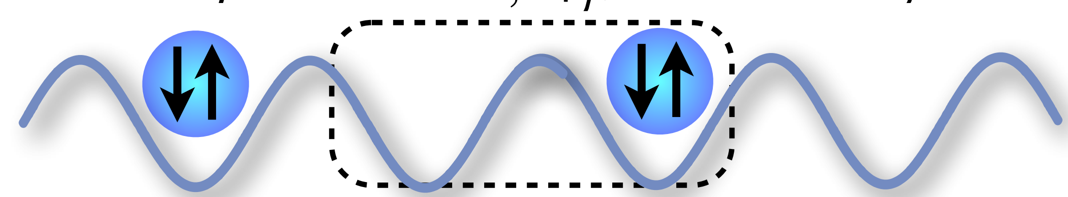

color singlet (density-density) interaction conservation number of excitation

$$\hat{N}_{\vec{r},\check{\mu}} = \hat{b}^{\alpha\dagger}_{\vec{r},\check{\mu}} \hat{b}^{\alpha}_{\vec{r},\check{\mu}} + \hat{b}^{\alpha\dagger}_{\vec{r}+\check{\mu},-\check{\mu}} \hat{b}^{\alpha}_{\vec{r}+\check{\mu},-\check{\mu}}$$

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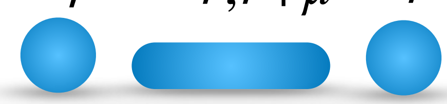

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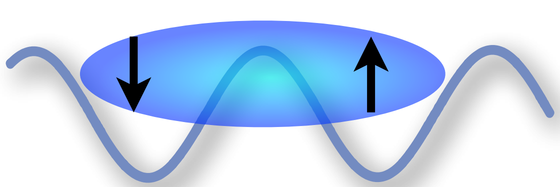

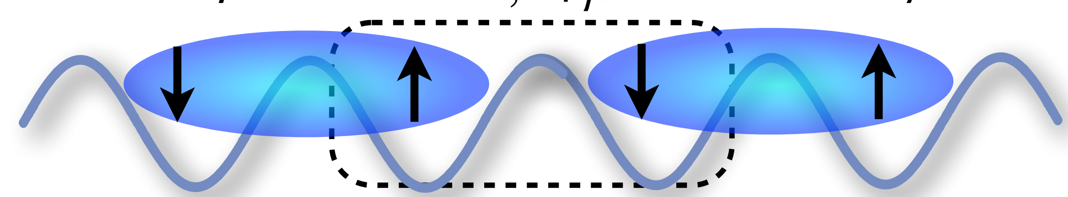

color singlet hopping

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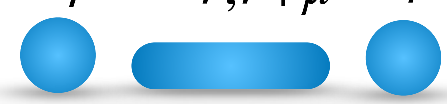
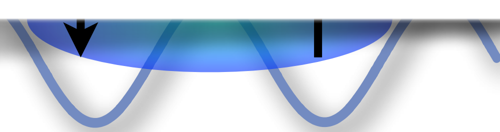


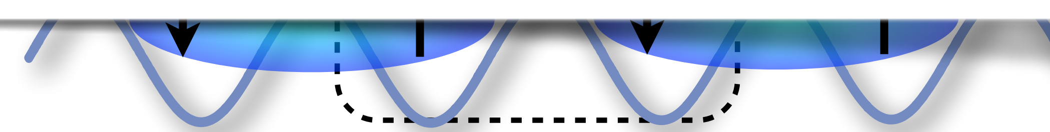
Features of the model:

Chiral dynamics in real time

Chiral SB and restoration at non-zero fermion density



$$+U\sum_{\vec r,\check\mu}\hat N^2_{\vec r,\check\mu}$$



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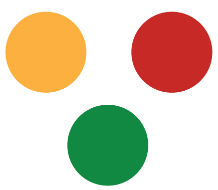
$SO(3)$ "Nuclear Physics" with ultracold Gases ☆

E. Rico [a, b], M. Dalmonte [c], P. Zoller [d], D. Banerjee [e, f], M. Bögli [e], P. Stebler [e], U.-J. Wiese [e]

SU(3) vs. SO(3)

quarks



gluons

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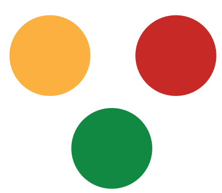
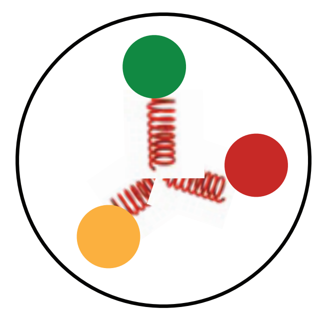
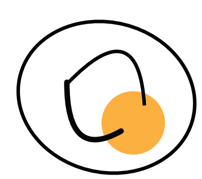


SU(3) baryon



gluons

SO(3) 'baryon'



Fermionic statistics

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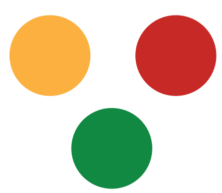

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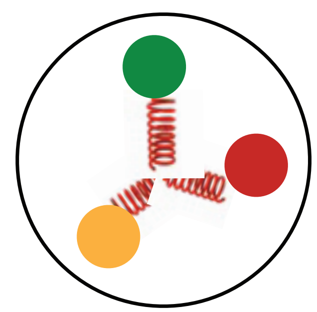
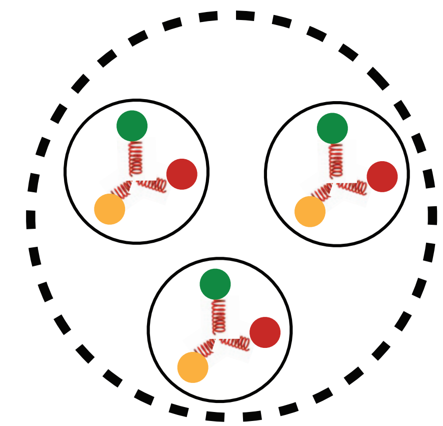
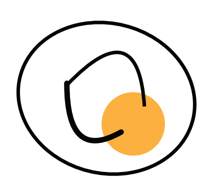


SU(3) nucleus

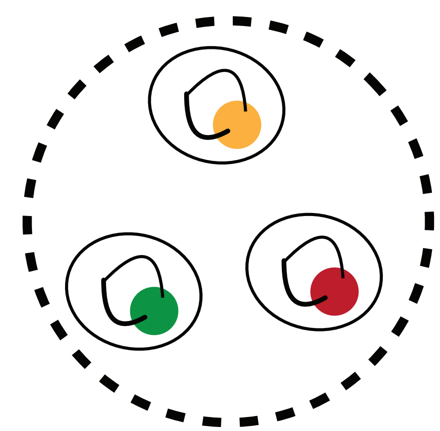


SO(3) 'baryon'



Fermionic statistics

SO(3) nucleus



Bound states of baryons

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Tensor product
(no extra constraint)

$$\hat{O}^{\alpha\beta}_{\vec{r},\vec{r}+\check{\mu}} = \hat{\sigma}^{\alpha}_{\vec{r},\check{\mu}} \otimes \hat{\sigma}^{\beta}_{\vec{r}+\check{\mu},-\check{\mu}}$$

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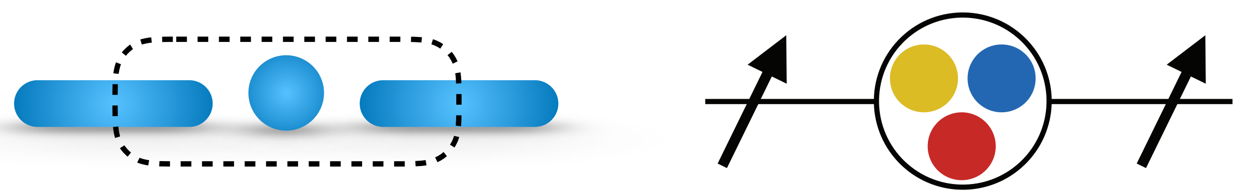

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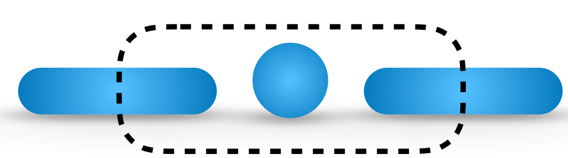

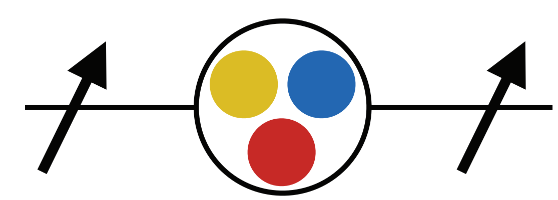

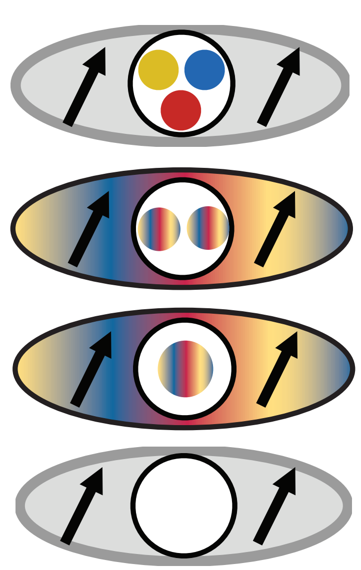

Gauge invariant Hilbert space
Singlet among the matter and gauge fields

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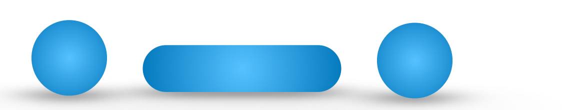

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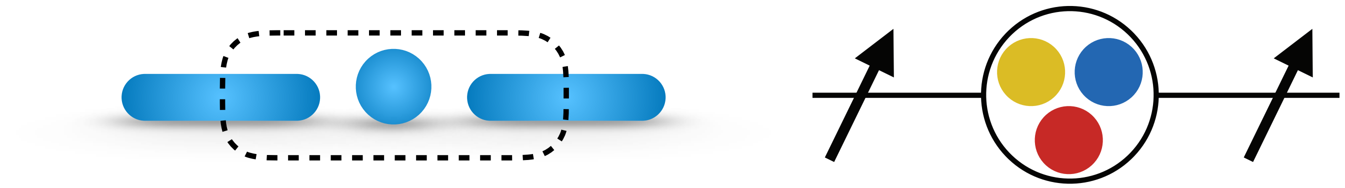

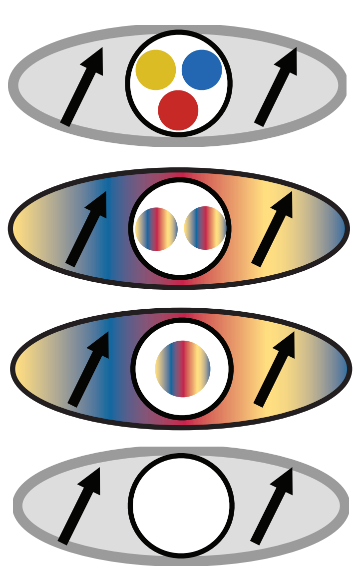

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$$\hat{\psi}^{\alpha\dagger}_{\vec{r}}\hat{\psi}^{\alpha}_{\vec{r}} \mapsto \hat{S}^{(3)}_{\vec{r}}$$

Exact encoding to a spin-3/2 model
Matter content maps to z spin component

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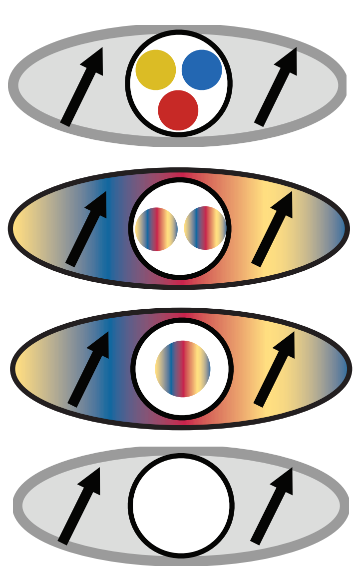
Features of the model:

SB of chiral symmetry and its restoration at finite baryon density
Existence of stable bound states (binding energy)



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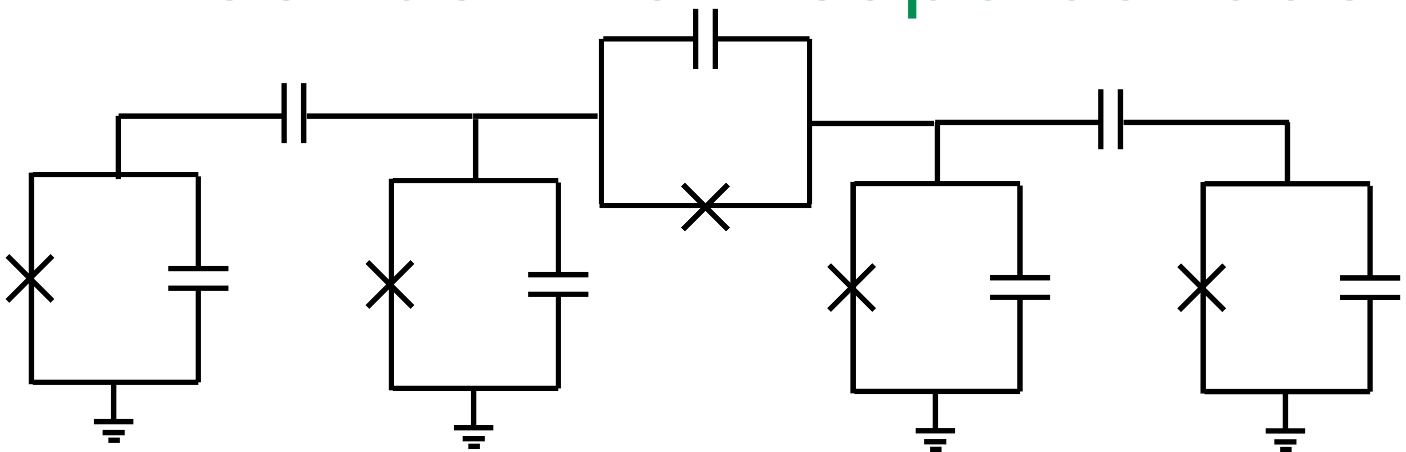
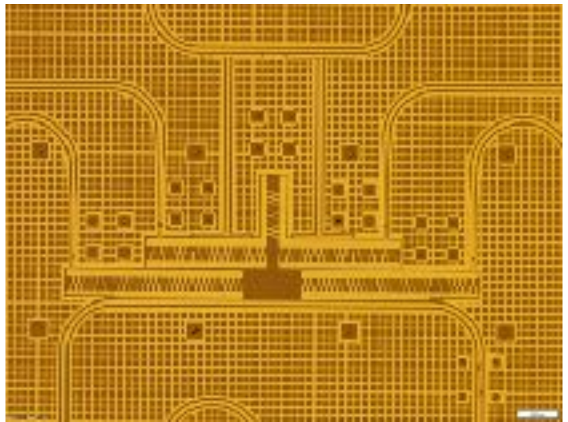
Exact encoding to a spin-3/2 model
Matter content maps to z spin component

- Tool-box from superconducting circuits





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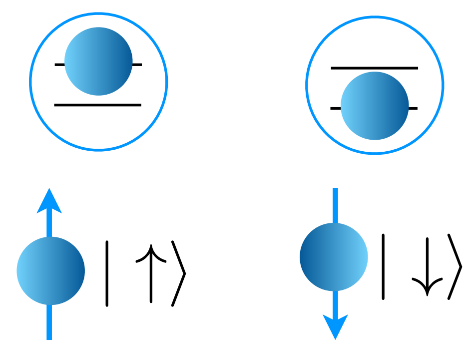
Implementation with superconducting circuits

Local degrees of freedom.-

Matter field:

$$\psi_x \mapsto \sigma_x^-$$
$$\psi_x^\dagger \mapsto \sigma_x^+$$



$$|0\rangle \mapsto |\downarrow\rangle$$
$$|1\rangle \mapsto |\uparrow\rangle$$

Implementation with superconducting circuits

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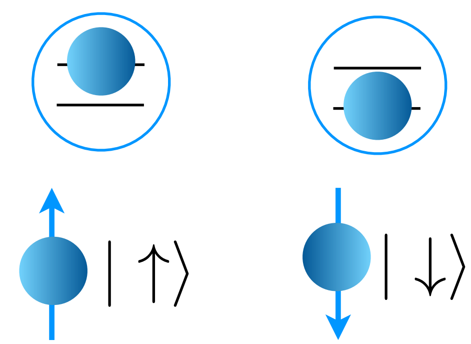
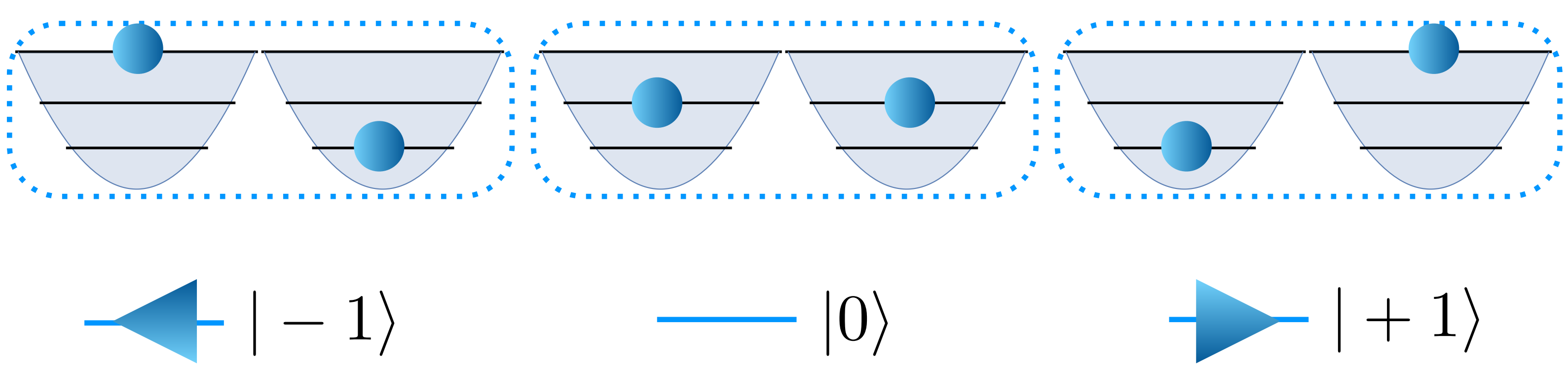


$$|0\rangle \mapsto |\downarrow\rangle \qquad |1\rangle \mapsto |\uparrow\rangle$$

Gauge field:



Implementation with superconducting circuits

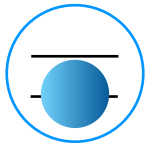
Local degrees of freedom.-

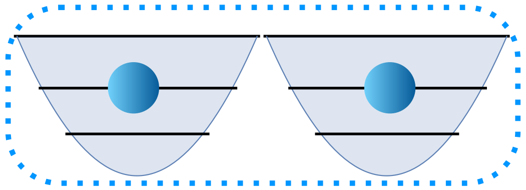
We need:

Tuneable (spectrum) device

- two-level atom (anharmonic)
- cavity (harmonic)

Coherent dynamics (low dissipation)





Implementation with superconducting circuits

Local degrees of freedom.-

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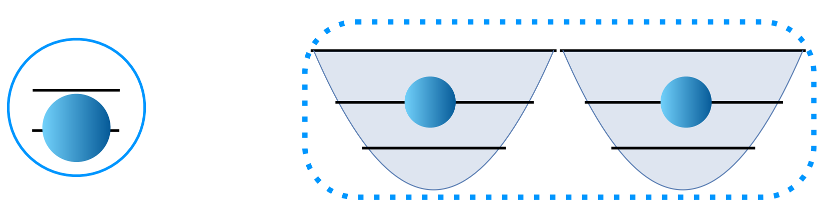
We need:

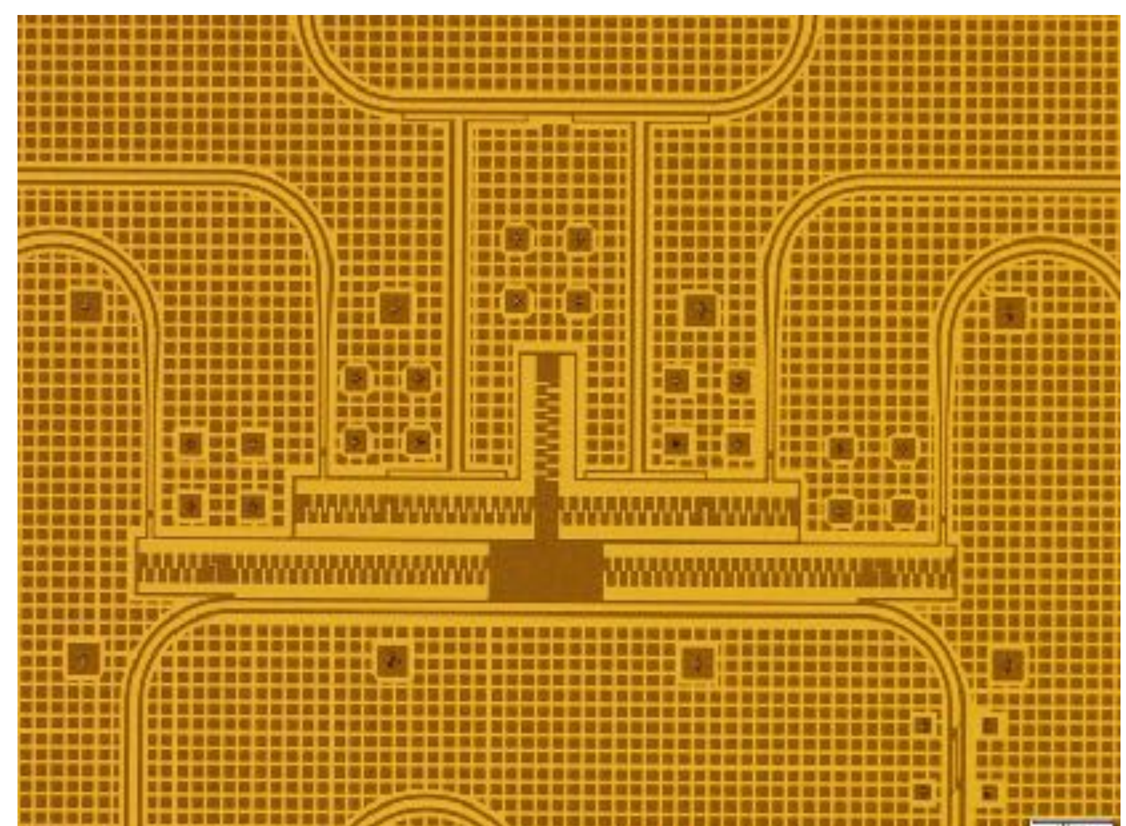
Tuneable (spectrum) device

two-level atom (anharmonic)
cavity (harmonic)

Coherent dynamics (low dissipation)



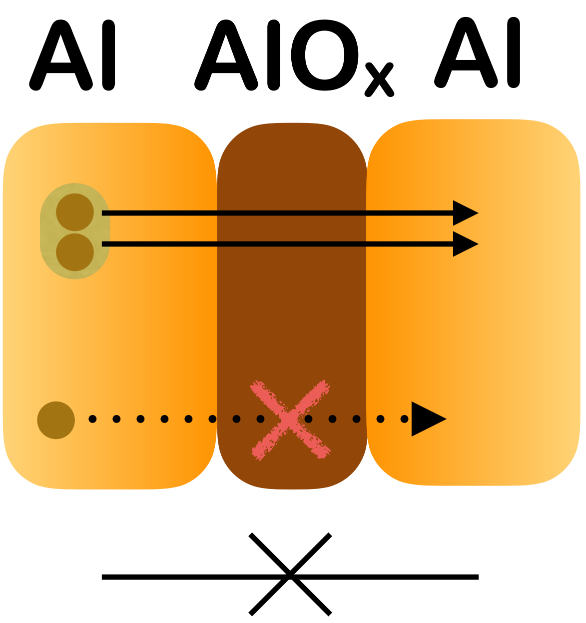
Chris Wilson



Ingredients from superconducting circuits

Josephson tunnelling:

- couple two superconductors via oxide layer
- oxide layer acts as tunnelling barrier
- superconducting gap inhibits electron tunnelling



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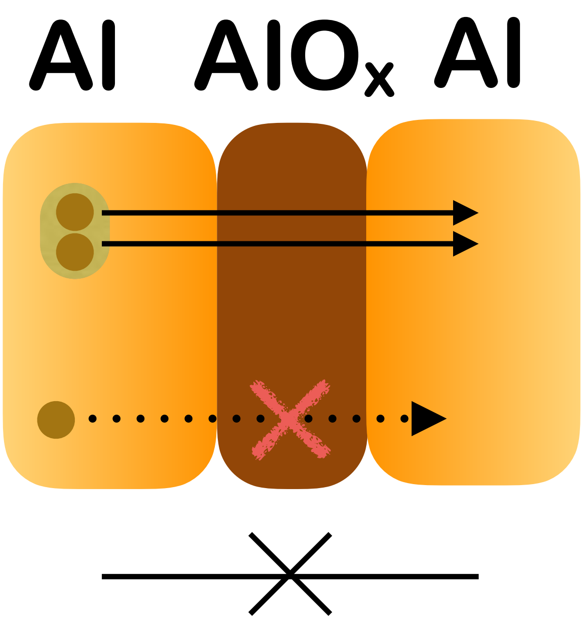

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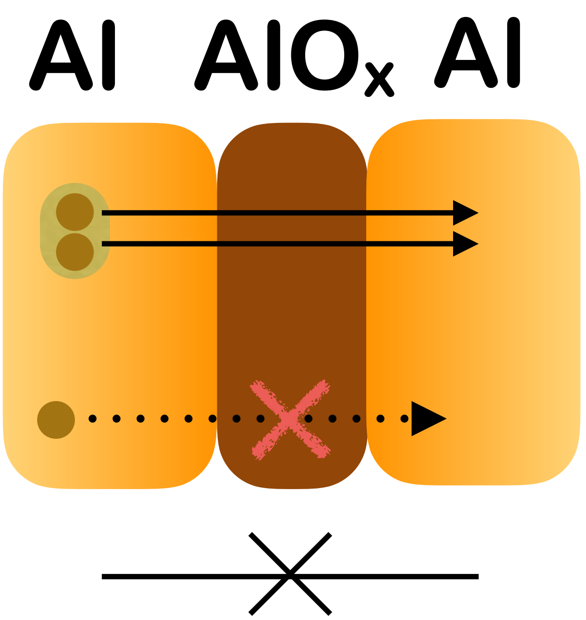
Josephson Hamiltonian:

$$H_J = -\frac{E_J}{2}\sum_n \left[|n\rangle\langle n+1| + |n+1\rangle\langle n| \right]$$

Ingredients from superconducting circuits



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$$H_J = -\frac{E_J}{2} \sum_n \left[|n\rangle\langle n+1| + |n+1\rangle\langle n| \right]$$

$$= -E_J \cos\phi$$

written in terms of the conjugate variable
(Fourier transform)
Physically: difference of the SC phases

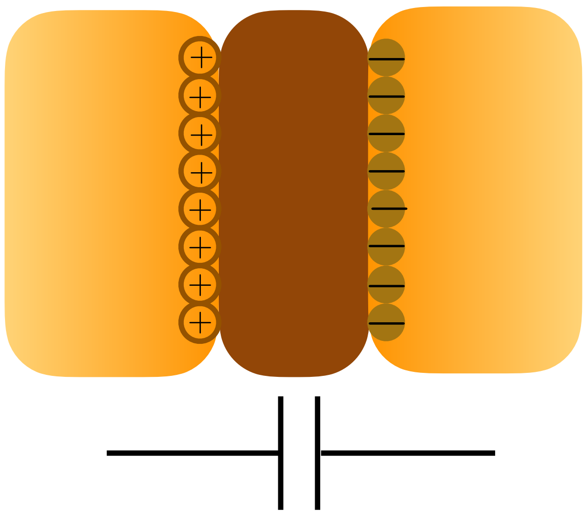
$$[\phi, n] = i$$

Ingredients from superconducting circuits

Local degrees of freedom.-

Charging hamiltonian of the SC: Junction also acts as a capacitor

$$H = \frac{(2e)^2}{2C} n^2 = 4E_C n^2$$



Ingredients from superconducting circuits

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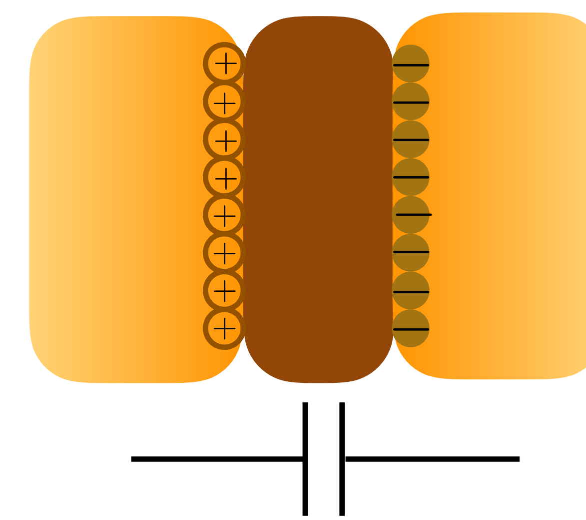
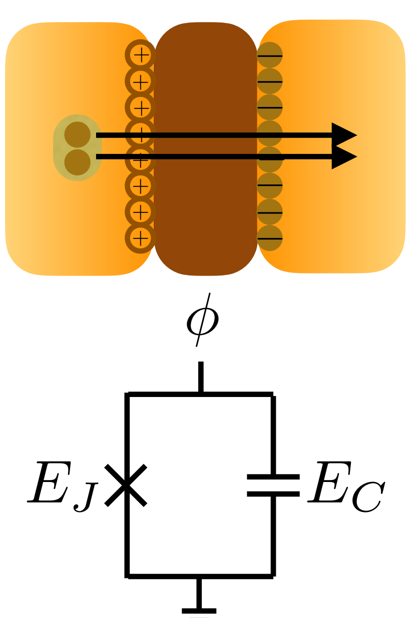
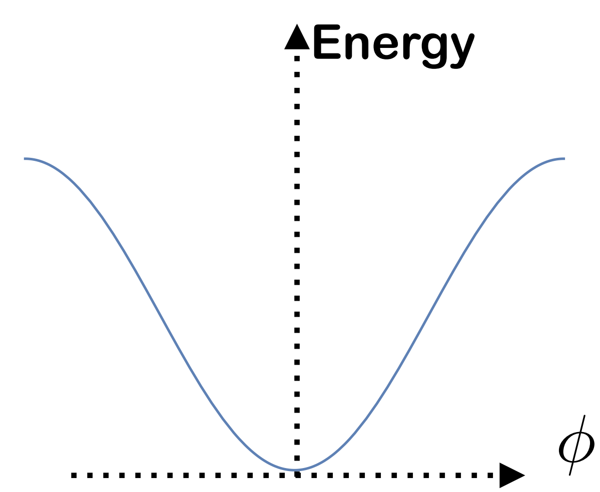


Non-linear oscillator - anharmonic cavity - Josephson junction:



$$H = 4E_C n^2 - E_J \cos\phi$$



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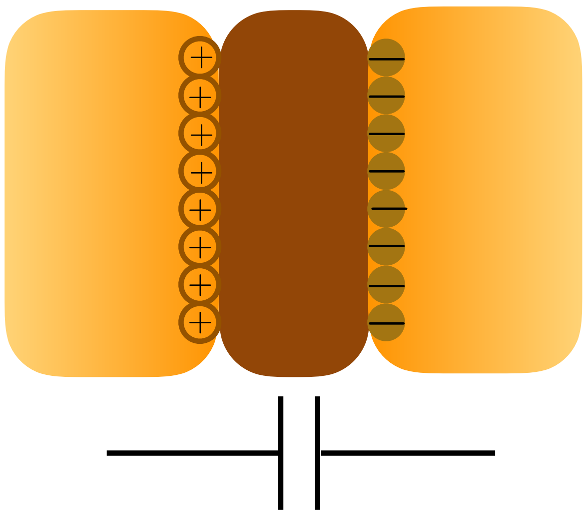

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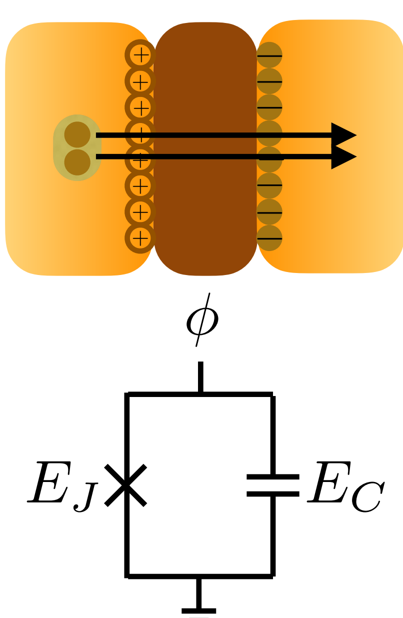
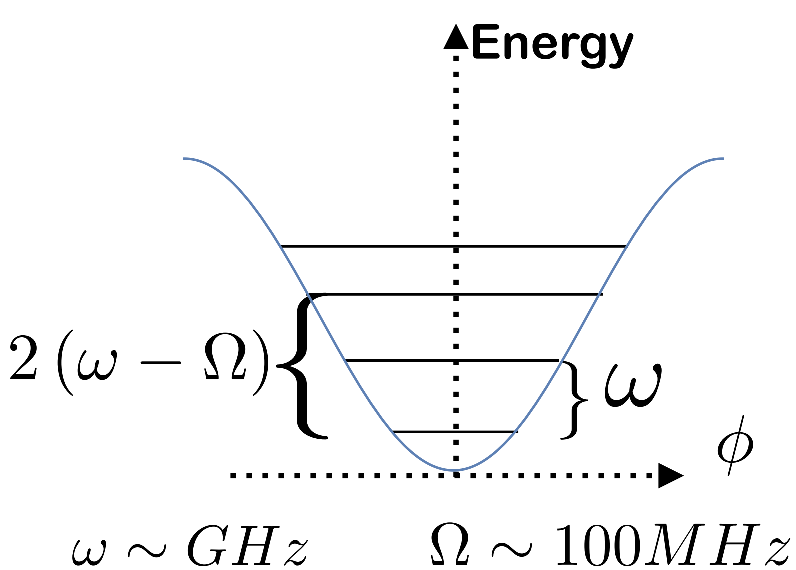


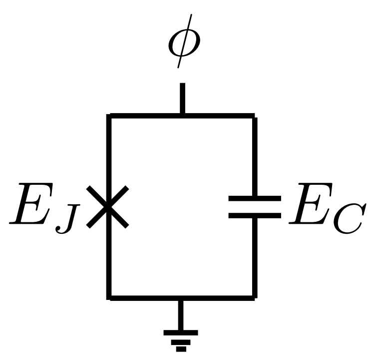
$$H = 4 E_C n^2 - E_J \cos \phi$$
$$= \omega b^\dagger b - \Omega b^{\dagger 2} b^2$$



Ingredients from superconducting circuits

Local degrees of freedom.-

Non-linear oscillator - anharmonic cavity - Josephson junction:



Important parameter: E_J/E_C

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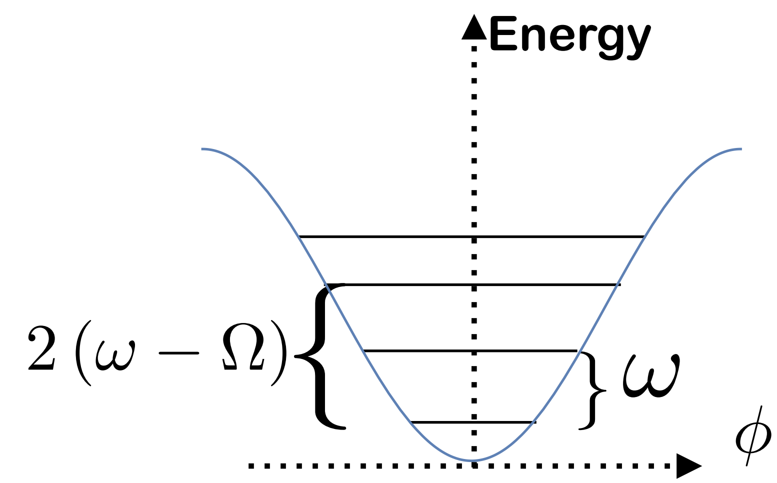
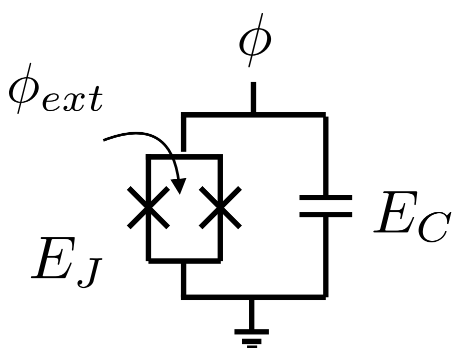


$E_C \rightarrow$ **Fixed by the geometry of the circuit**

Ingredients from superconducting circuits

Local degrees of freedom.-

Non-linear oscillator - anharmonic cavity - Josephson junction:



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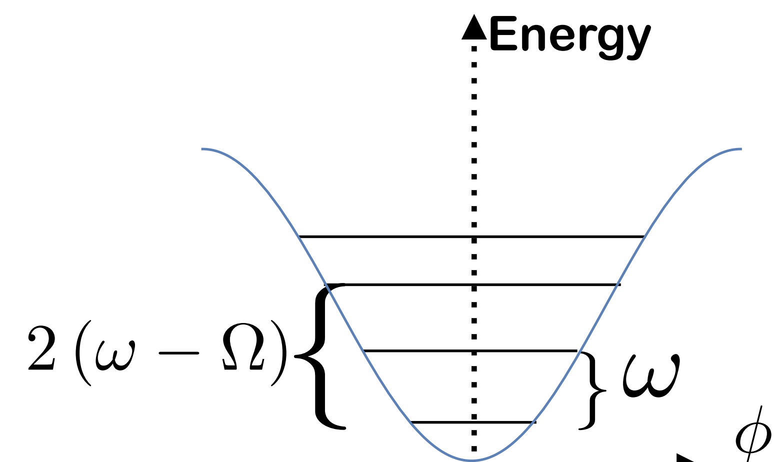


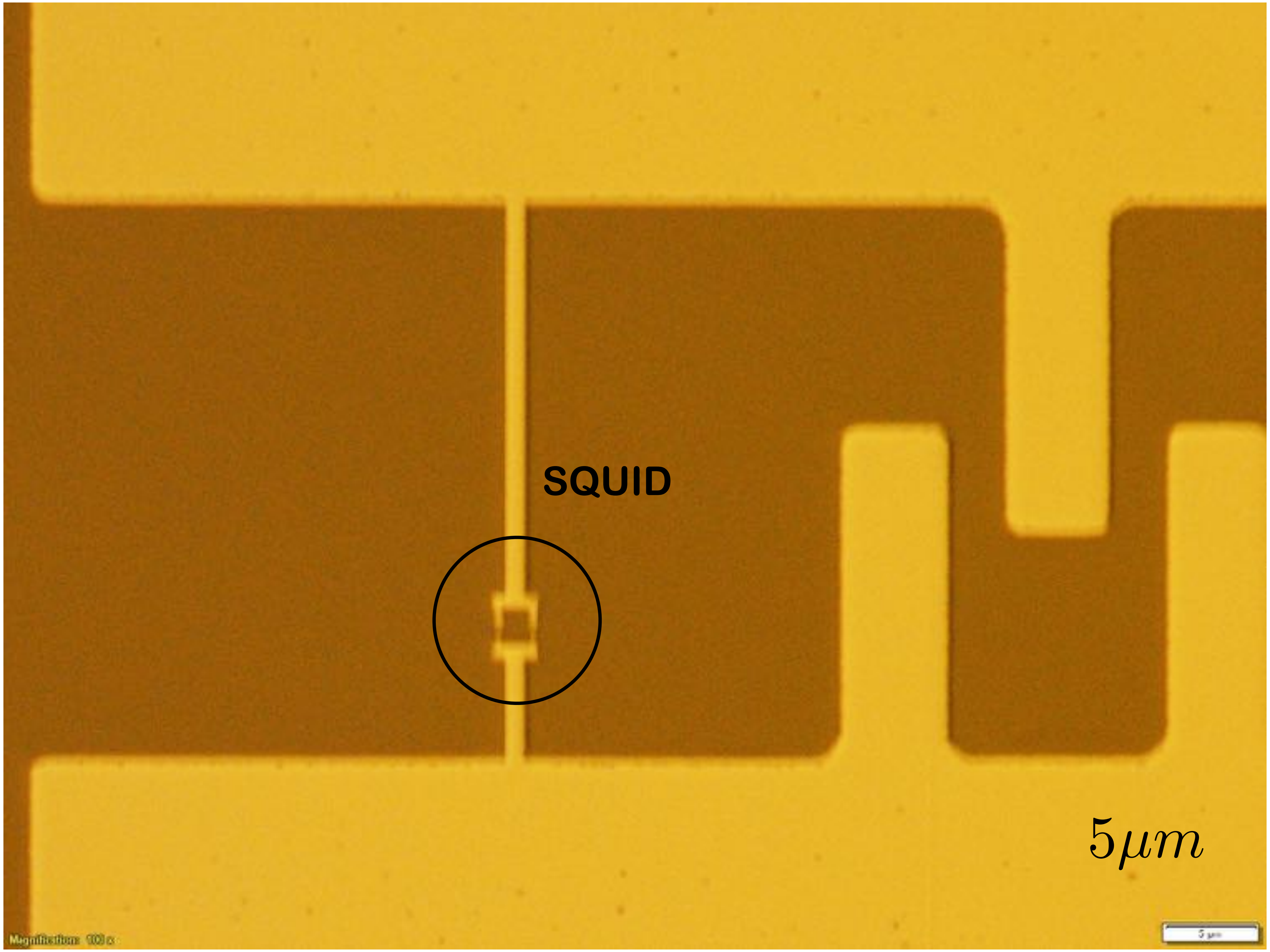
$E_C \rightarrow$ Fixed by the geometry of the circuit

$E_J \rightarrow$ Introduction of a SQUID makes the junction tuneable with an external flux

$$E_J(\phi_{ext}) = E_J^{\max} \cos(\phi_{ext})$$

$E_J/E_C \sim 20$ Transmon regime, maximum anharmonicity

Ingredients from superconducting circuits



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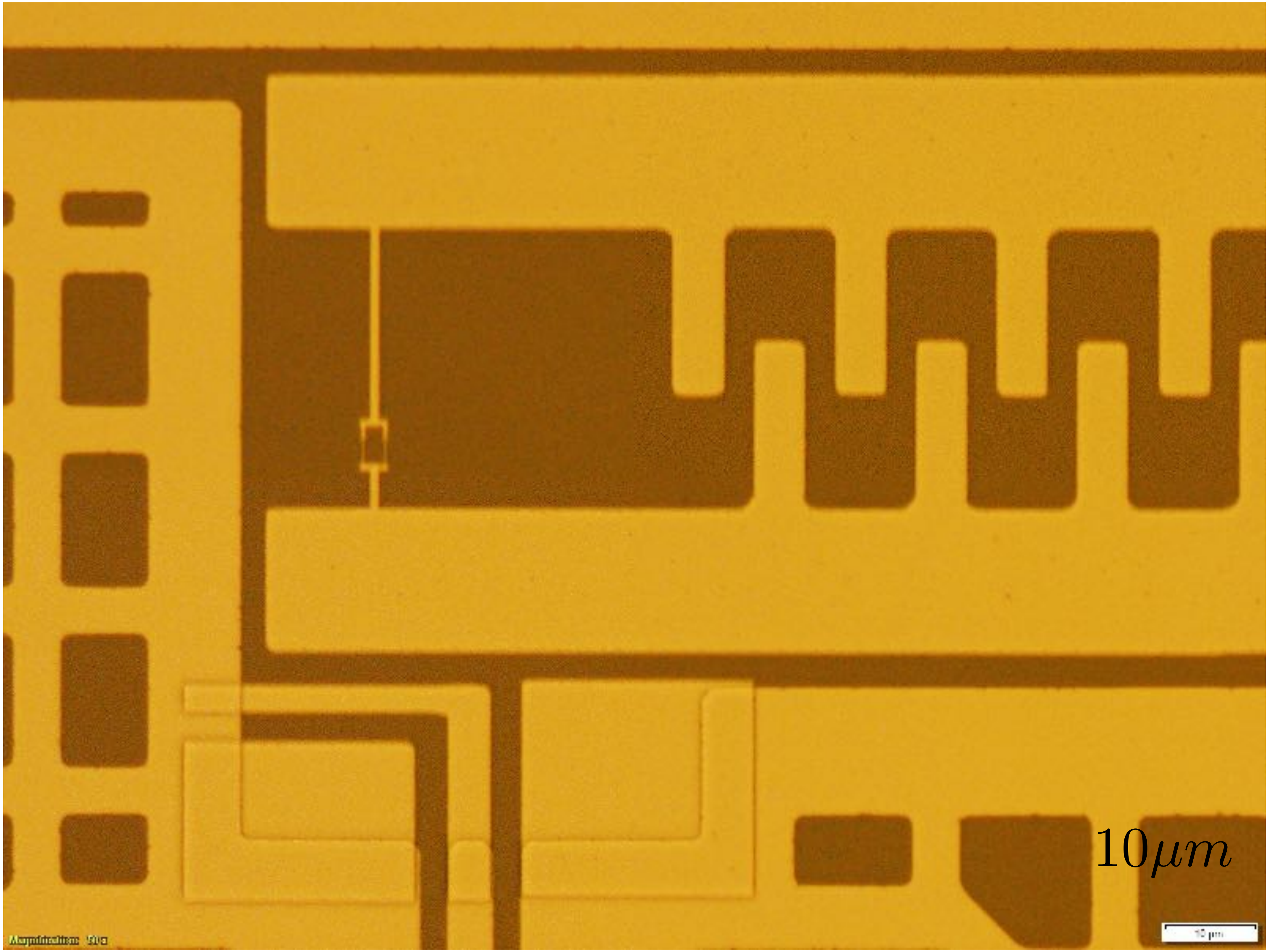

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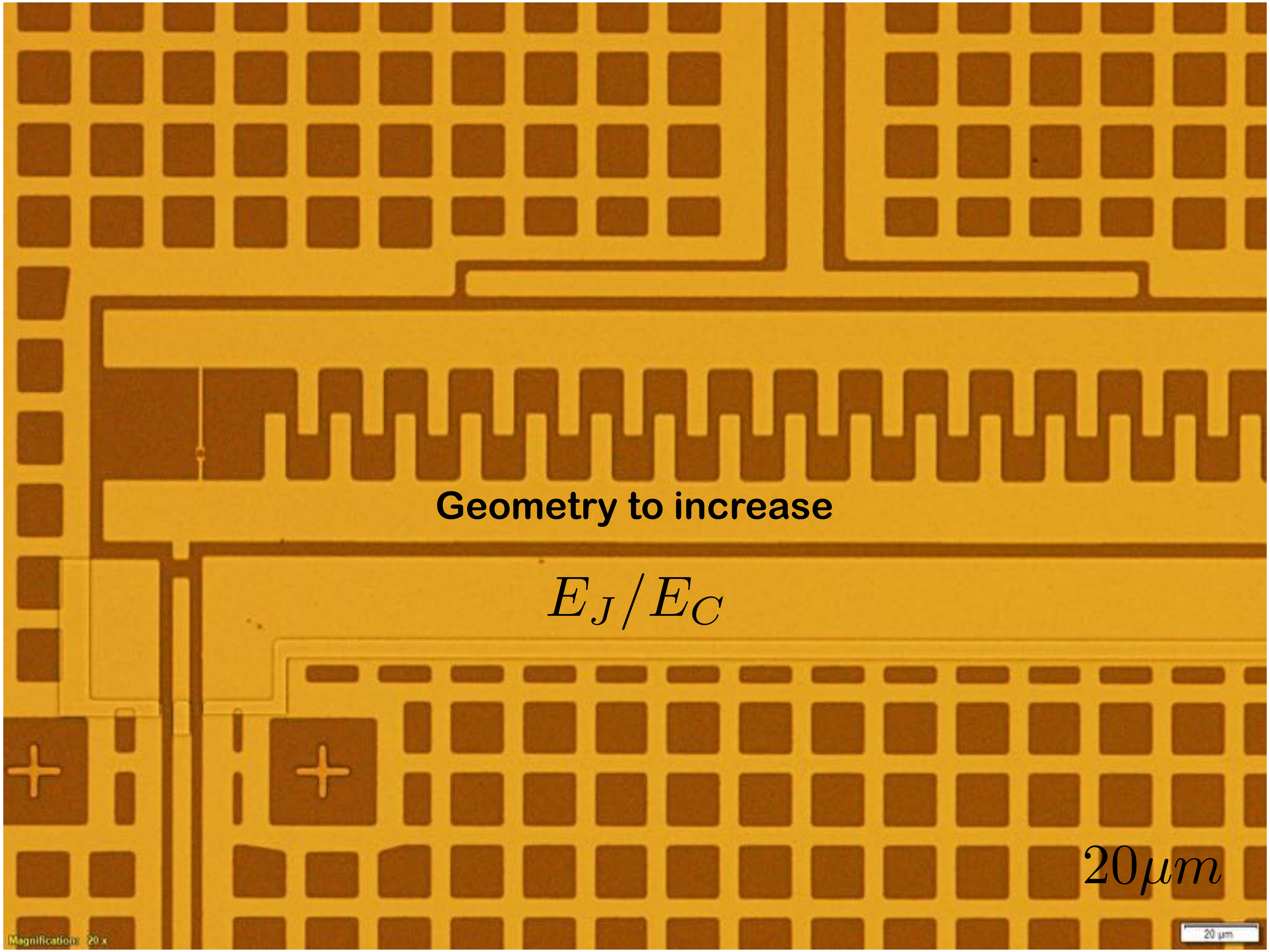
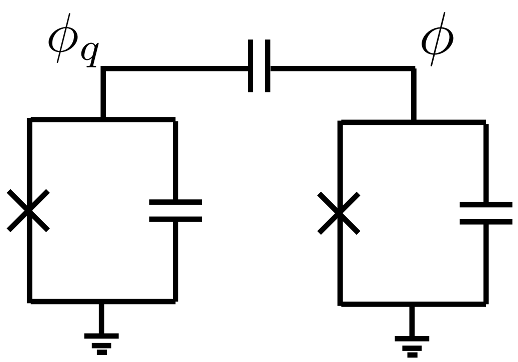


Ingredients from superconducting circuits

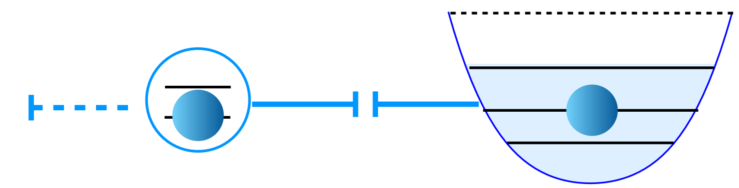
Two coupled Non-linear LC circuit:



qubit-cavity

$$L_{int} = \frac{C_g}{2}\left(\dot{\phi}_q - \dot{\phi}\right)^2$$

$$H_{int} \simeq \lambda\left(\sigma_q^+ b + \sigma_q^- b^\dagger\right)$$



Jaynes-Cummings Hamiltonian

Ingredients from superconducting circuits

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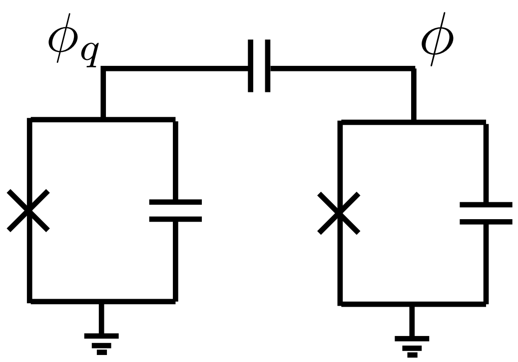

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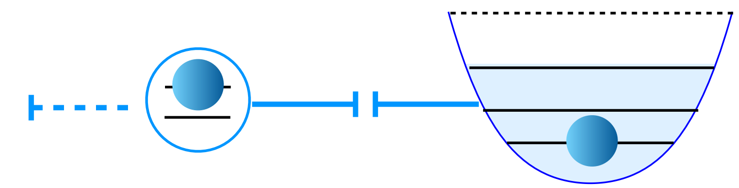
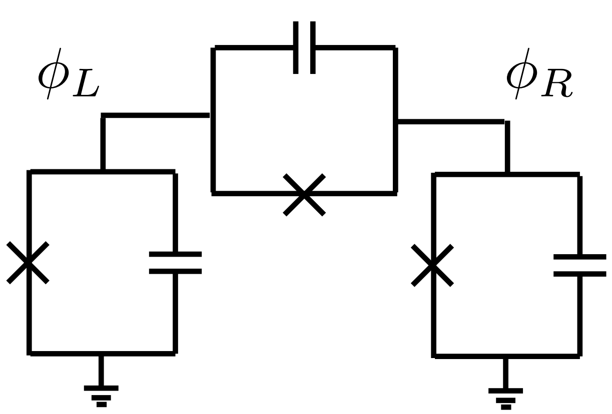
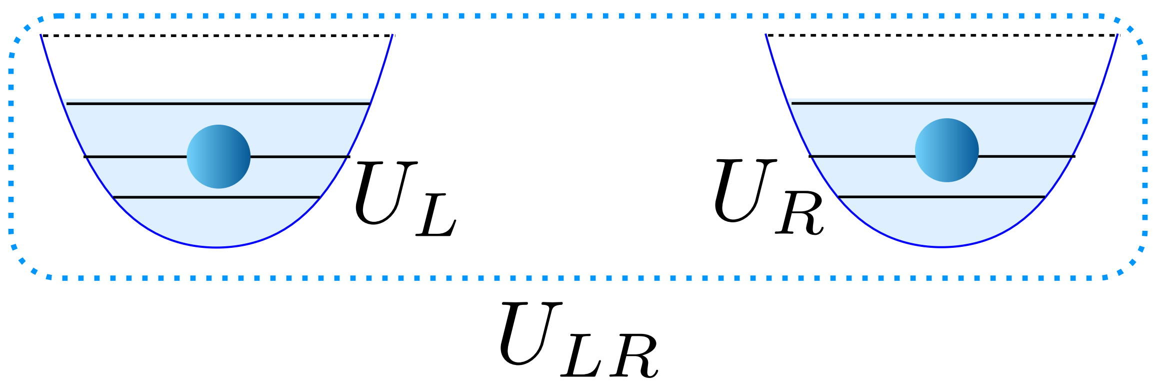


Jaynes-Cummings Hamiltonian



cavity-cavity



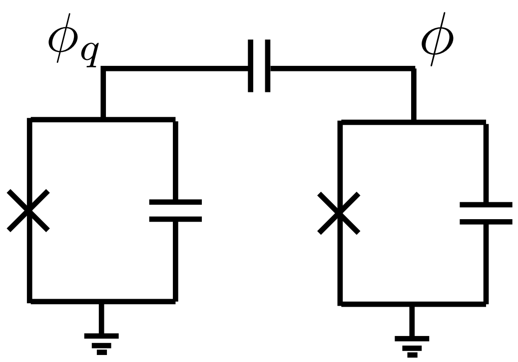
We need:

well-localised modes (no-tunnelling) - detuned cavities

Impose gauge constraint (conservation of excitations)

Ingredients from superconducting circuits

Two coupled Non-linear LC circuit:



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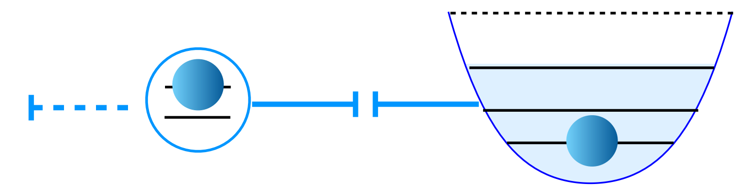

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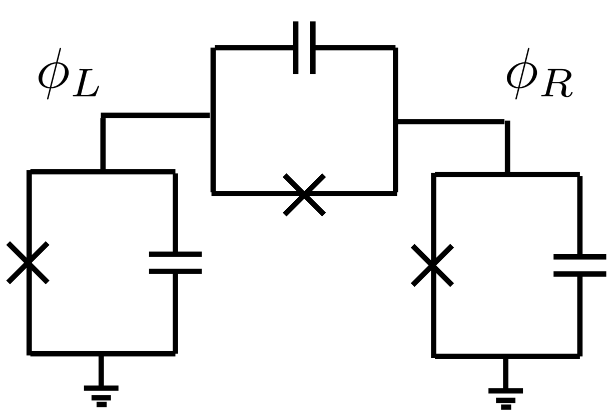
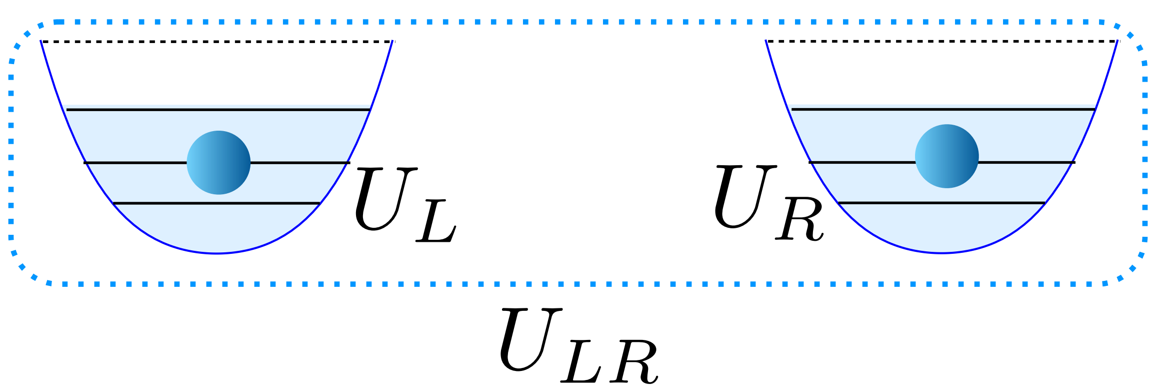


cavity-cavity



We need:

well-localised modes (no-tunnelling) - detuned cavities

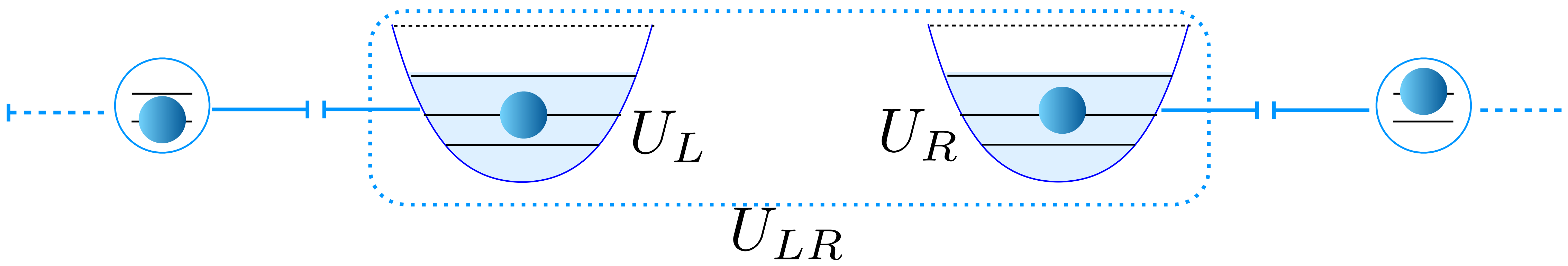
Impose gauge constraint (conservation of excitations)

$$H_{link} = \omega_L b_L^\dagger b_L + \omega_R b_R^\dagger b_R - U_L\left(b_L^\dagger b_L\right)^2 - U_R\left(b_R^\dagger b_R\right)^2 - U_{LR} b_L^\dagger b_L b_R^\dagger b_R$$

$$= \frac{g^2}{8}\left(b_L^\dagger b_L - b_R^\dagger b_R\right)^2 + \delta\left(b_L^\dagger b_L + b_R^\dagger b_R\right) - W\left(b_L^\dagger b_L + b_R^\dagger b_R\right)^2$$

Integrating the different elements

Hamiltonian:



$$H = \lambda \left(\sigma_1^+ b_L + \sigma_2^+ b_R + \mathrm{h.c} \right) - W \left(n_L + n_R \right)^2$$

Integrating the different elements

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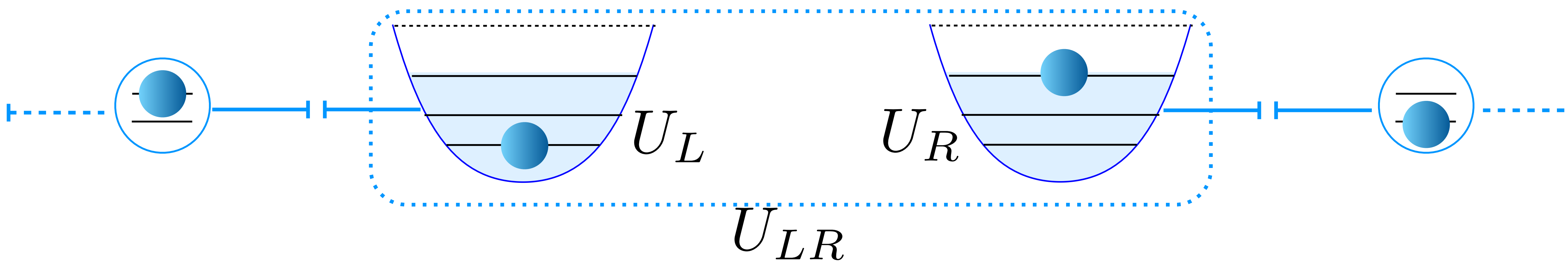
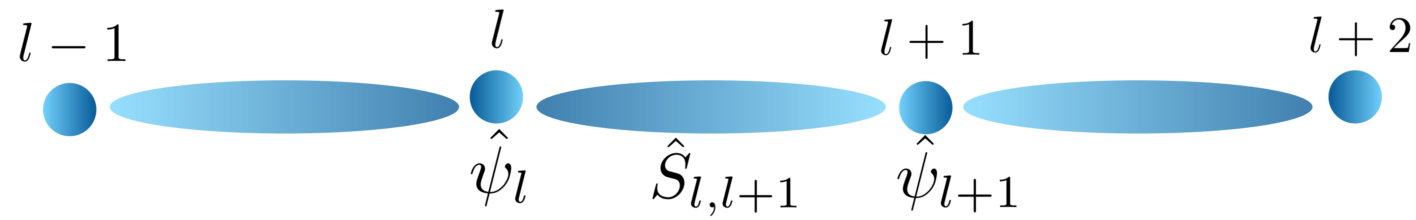


$$H = \lambda \left(\sigma_1^+ b_L + \sigma_2^+ b_R + \mathrm{h.c}\right) - W \left(n_L + n_R\right)^2$$

$$\rightarrow -\frac{\lambda^2}{W}\left(\sigma_1^+ b_L b_R^\dagger \sigma_2^- + \mathrm{h.c.}\right)$$

Matter - gauge interaction
= hopping of fermions mediated by a quantum link
= correlated hopping of fermions and Schwinger modes

Integrating the different elements



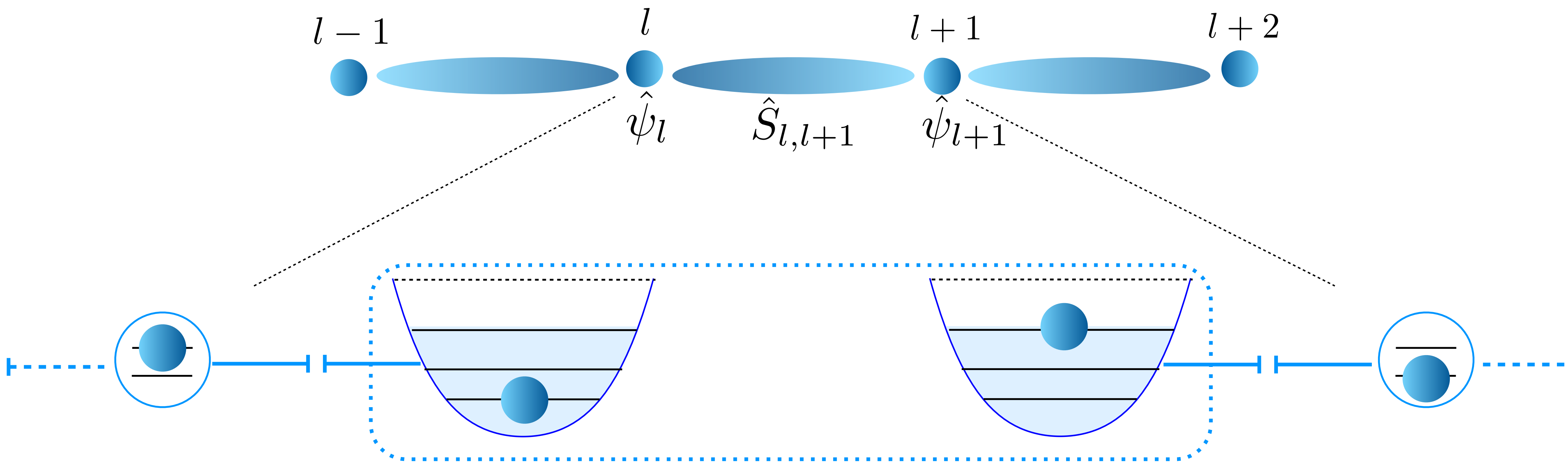
$$H = \frac{g^2}{2} \sum_x \left(S^{(3)}_{x,x+1} \right)^2 - t \sum_x \left(\sigma^+_x S^+_{x,x+1} \sigma^-_{x+1} + \text{h.c.} \right) + m \sum_x (-1)^x \sigma^+_x \sigma^-_x$$

Electric term (on-site energy)

Matter-gauge coupling (correlated hopping)

Staggered mass (energy off-set)

Integrating the different elements



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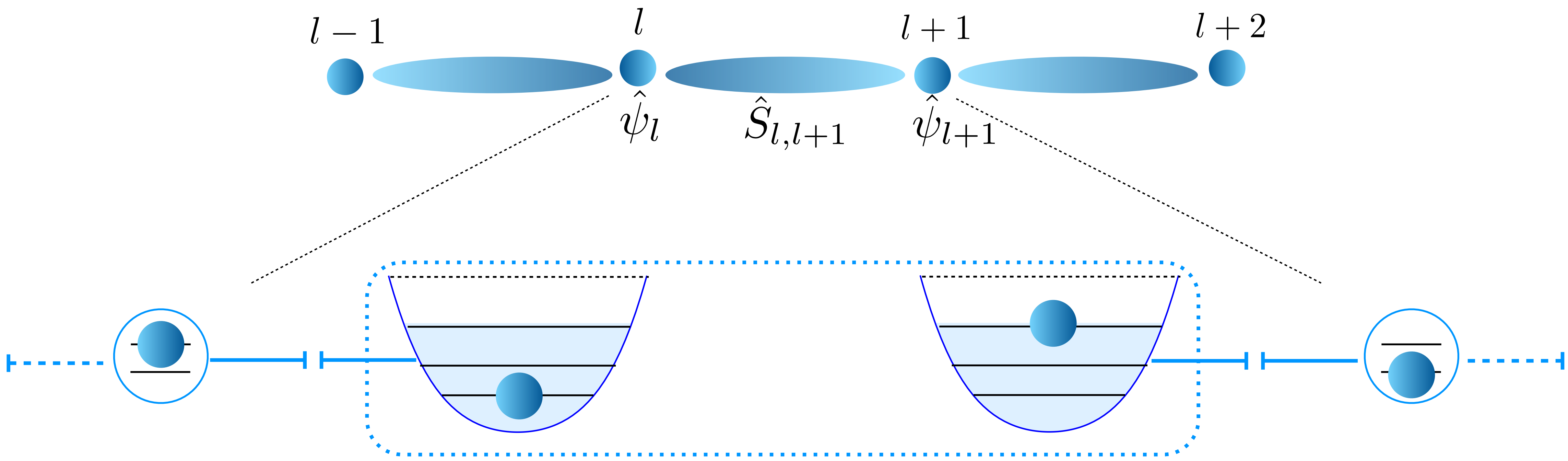

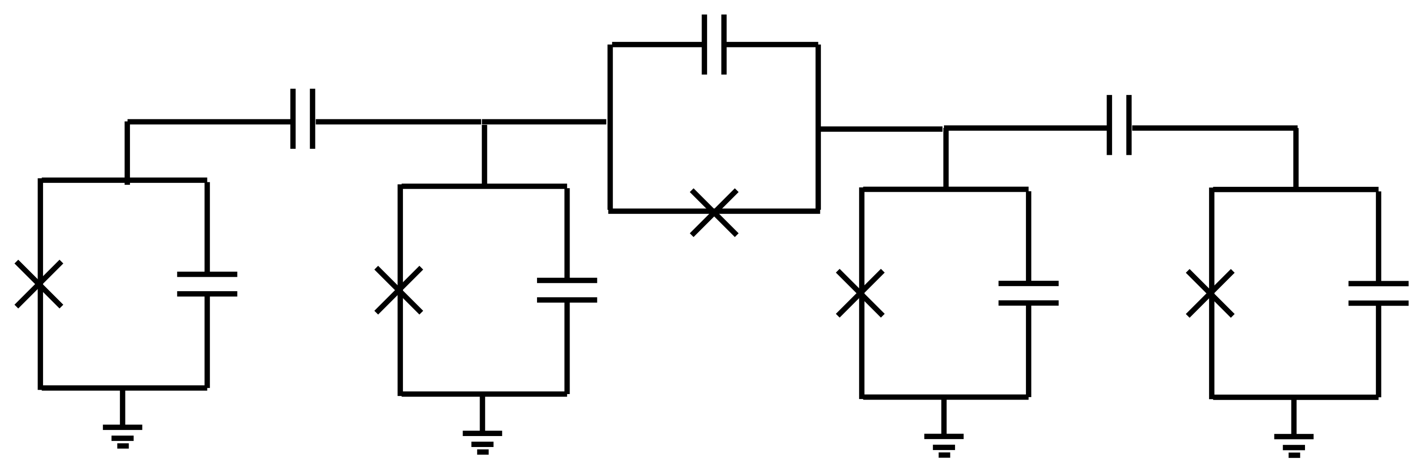

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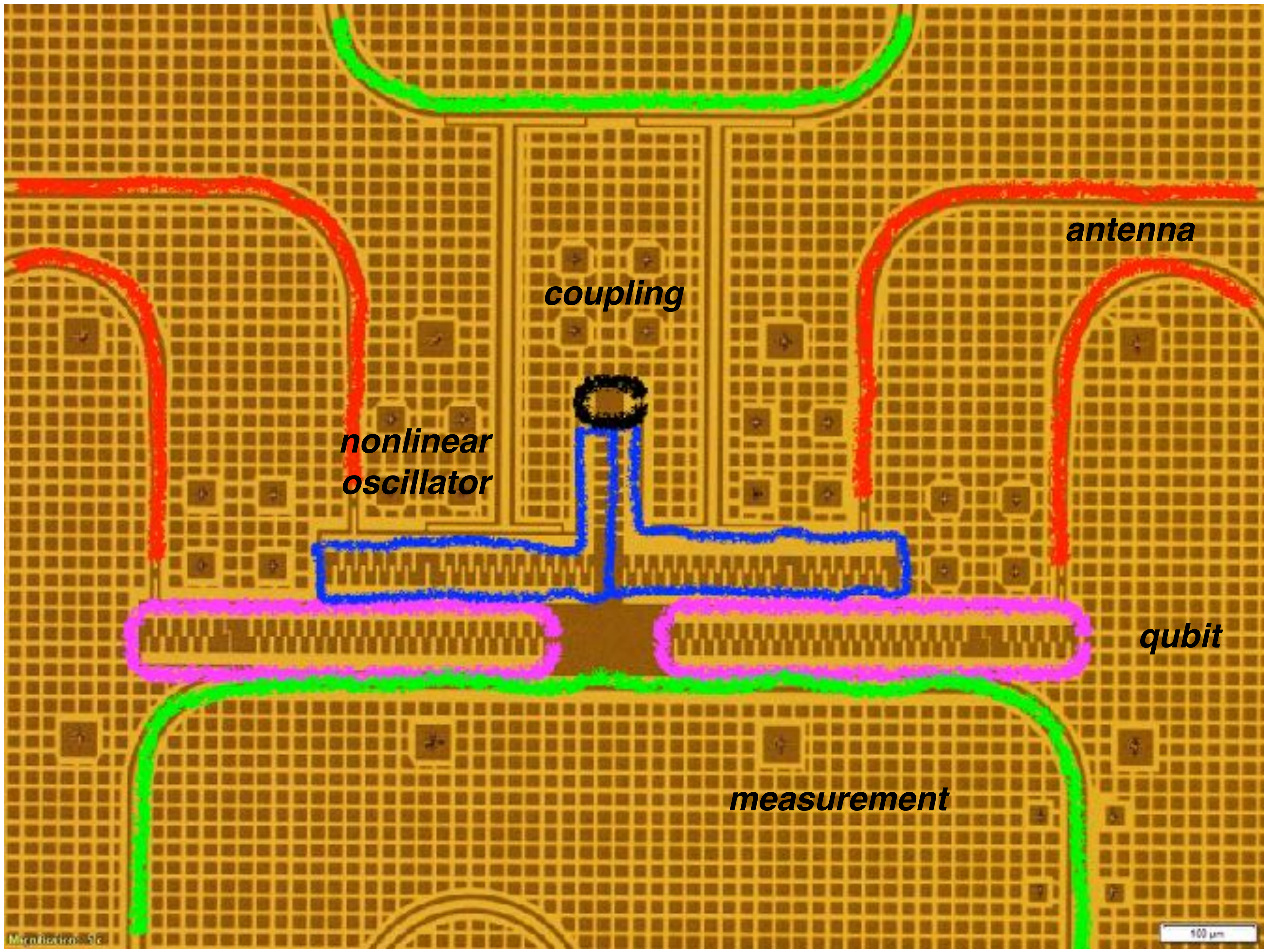

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Electric term (on-site energy)

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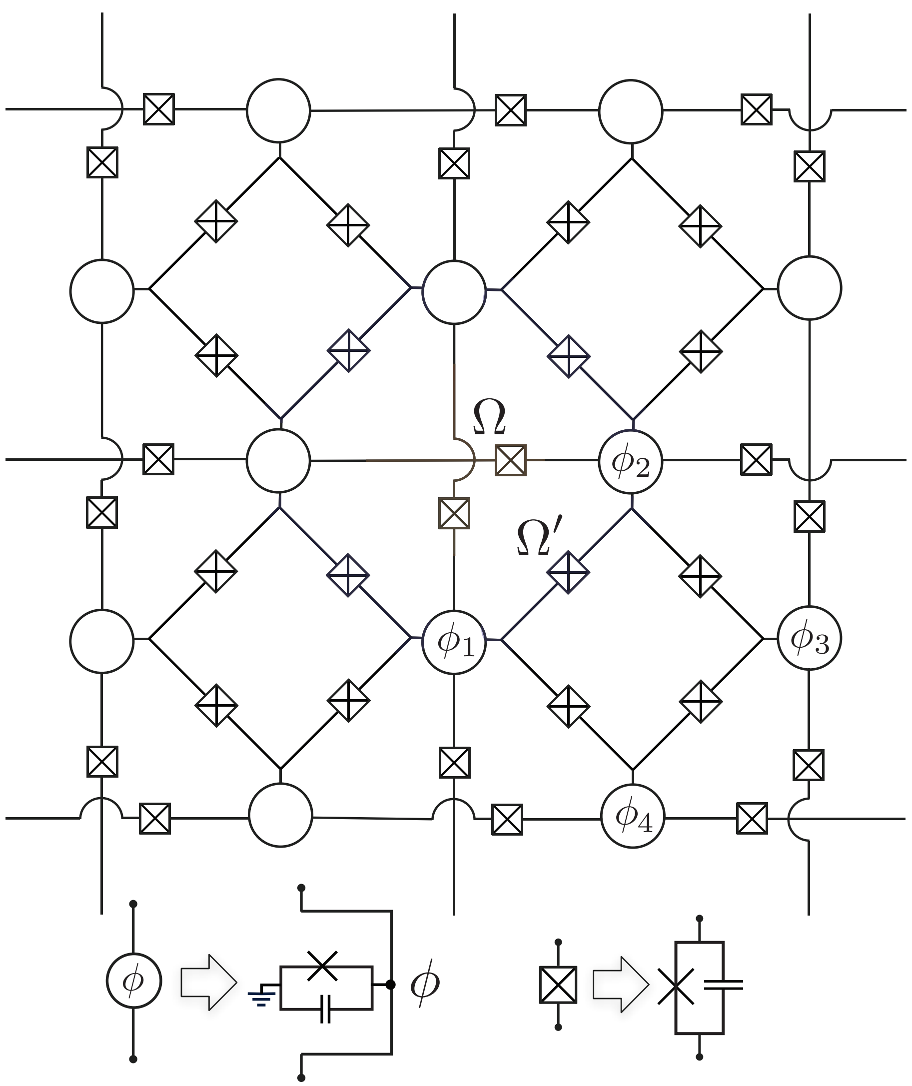
Two-dimensional lattice gauge theories with superconducting quantum circuits

D. Marcos[a,*], P. Widmer[b], E. Rico[c], M. Hafezi[d,e], P. Rabl[f], U.-J. Wiese[b], P. Zoller[a,g]

Annals of Physics 351 (2014) 634–654

Based on transmon devices:



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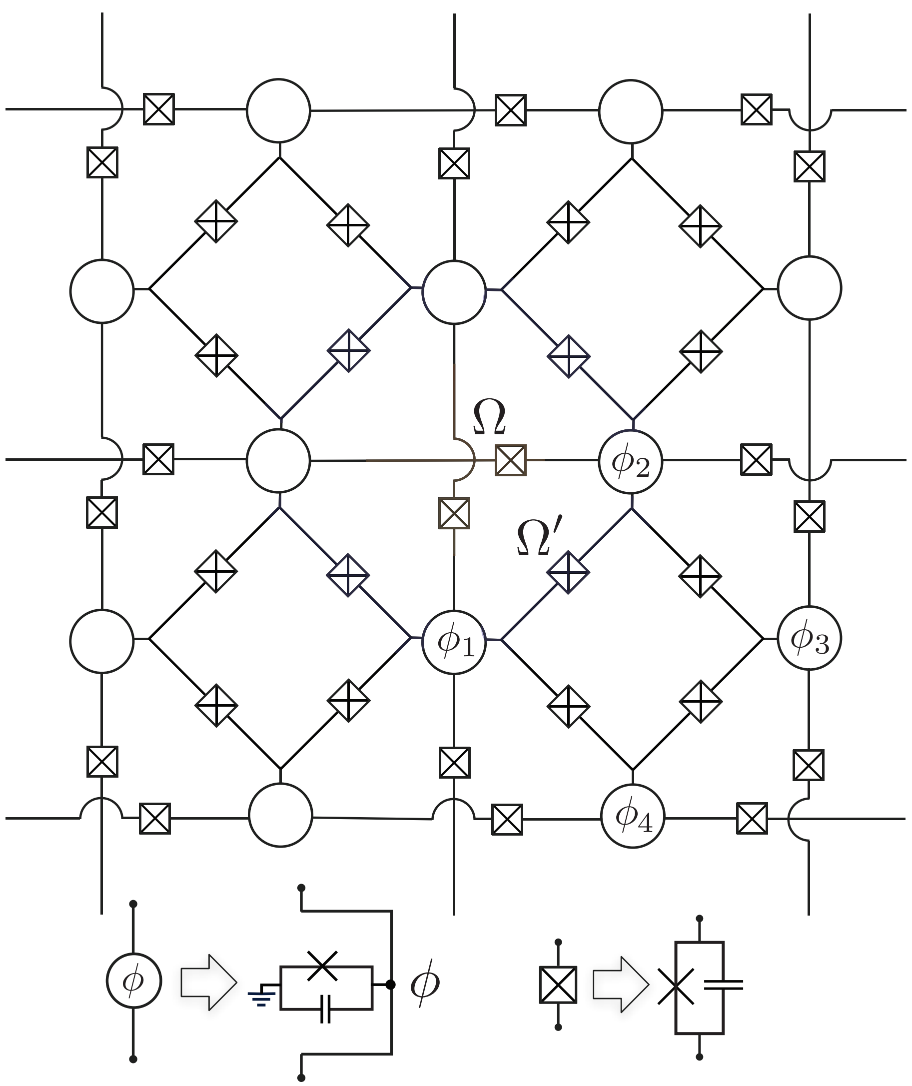
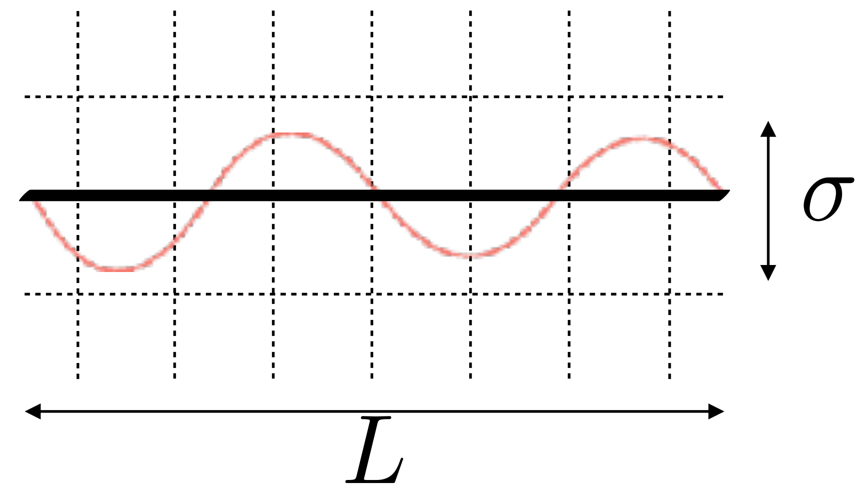
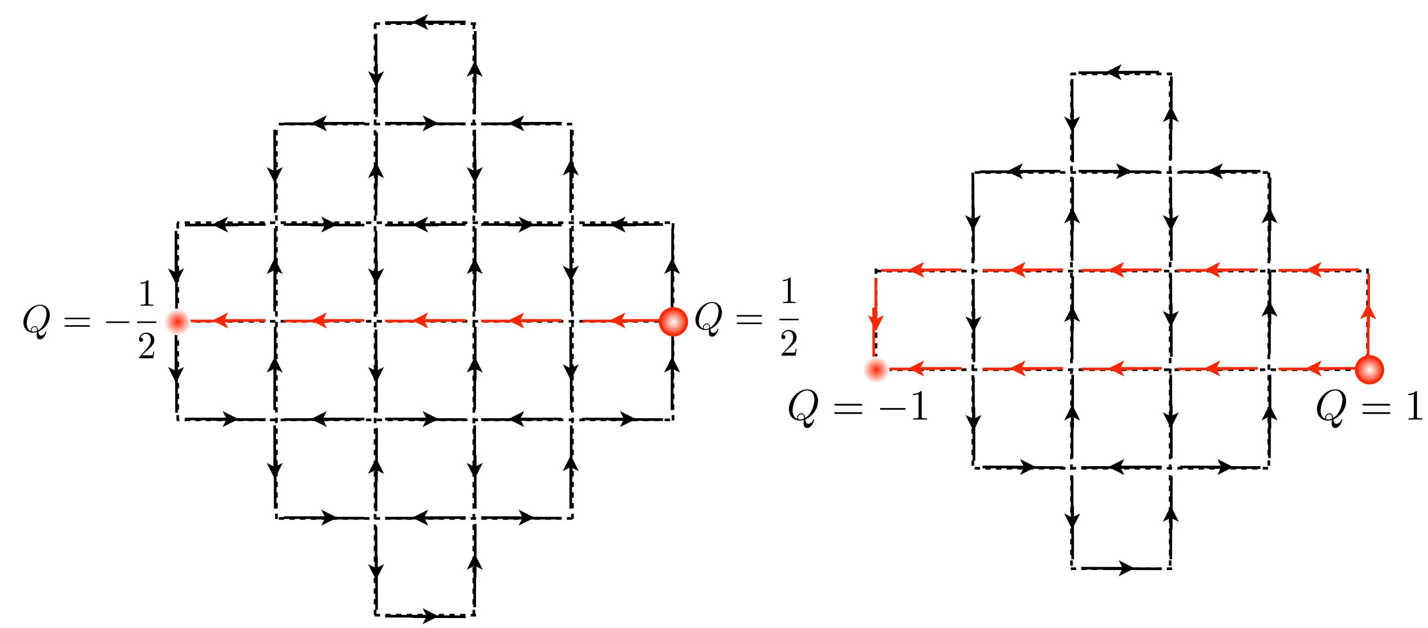
Based on transmon devices:

simulate string physics on a chip







University of the Basque Country

PRL **117,** 240504 (2016) PHYSICAL REVIEW LETTERS week ending 9 DECEMBER 2016

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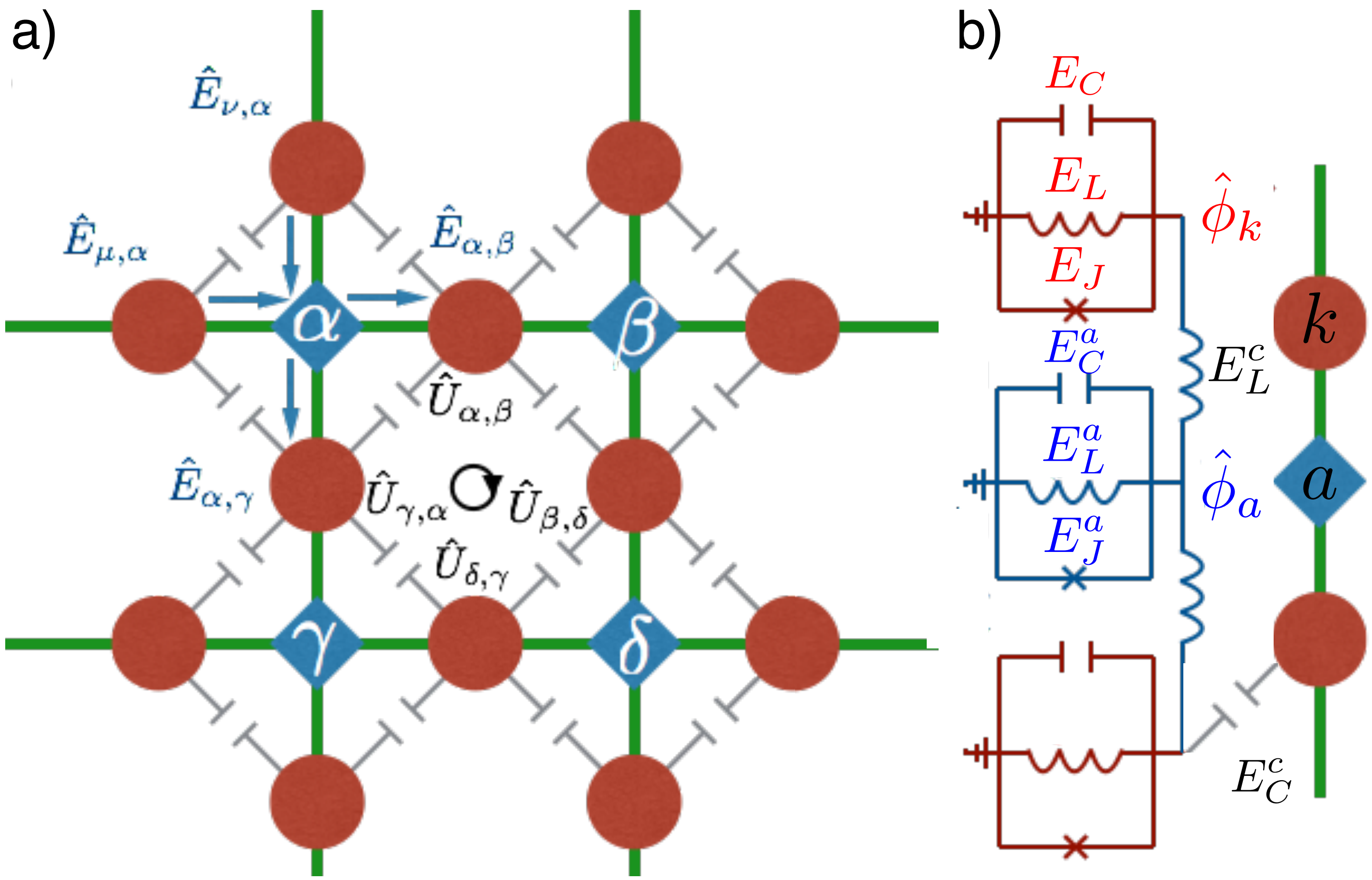
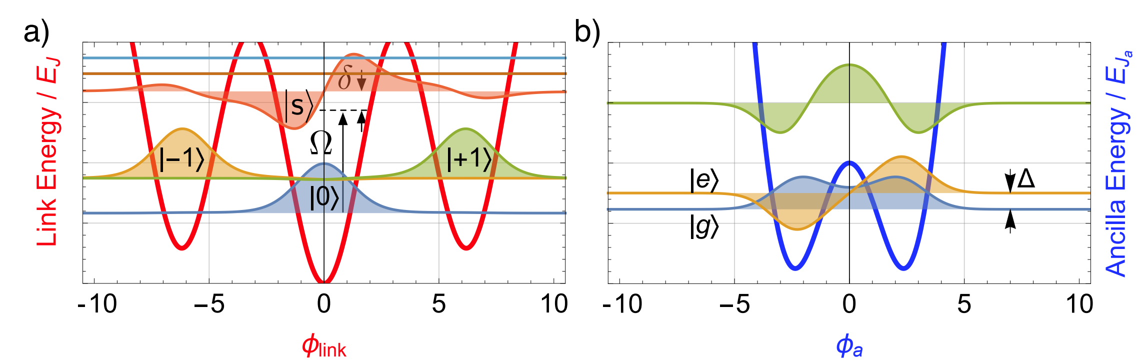
Loops and Strings in a Superconducting Lattice Gauge Simulator

G. K. Brennen,[1] G. Pupillo,[2] E. Rico,[3,4] T. M. Stace,[5] and D. Vodola[2]



Based on fluxonium devices:



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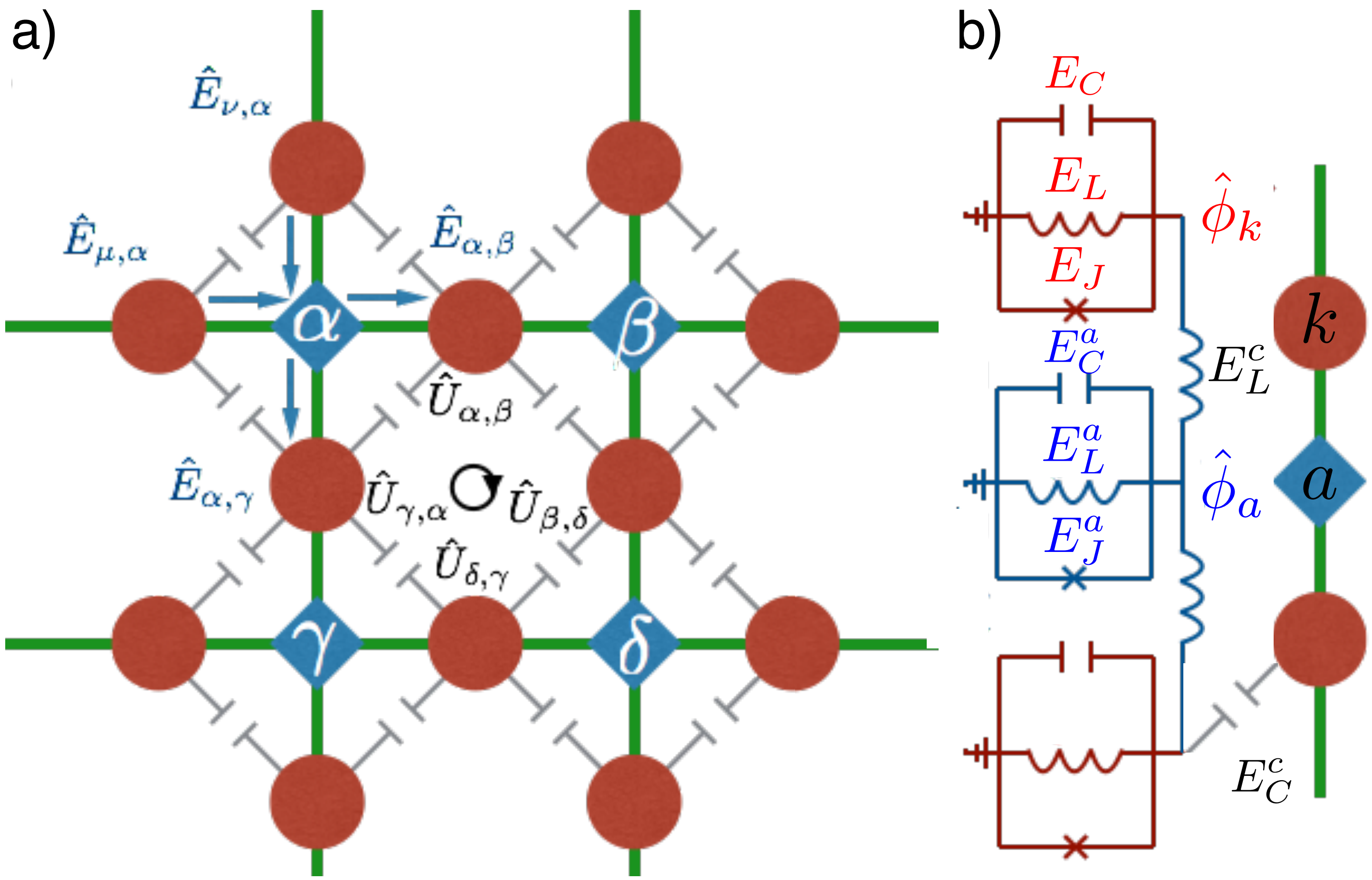

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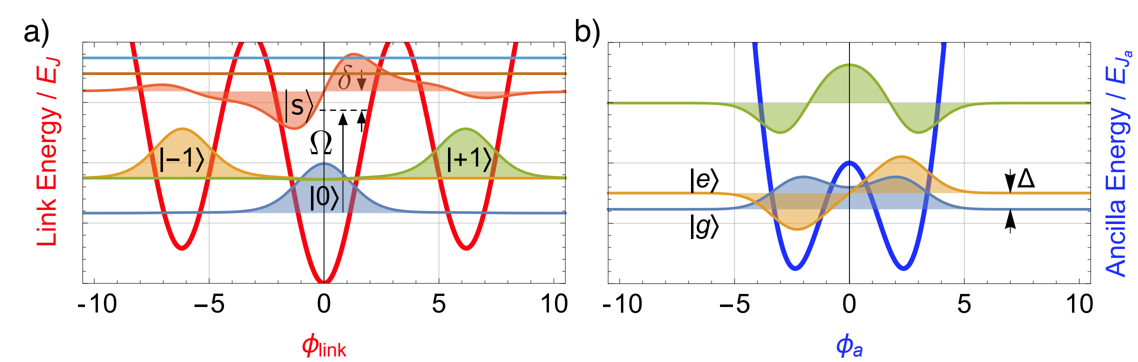
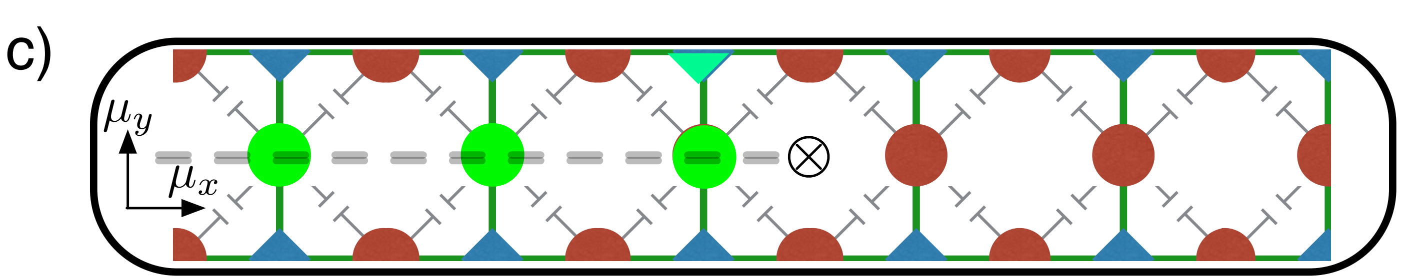
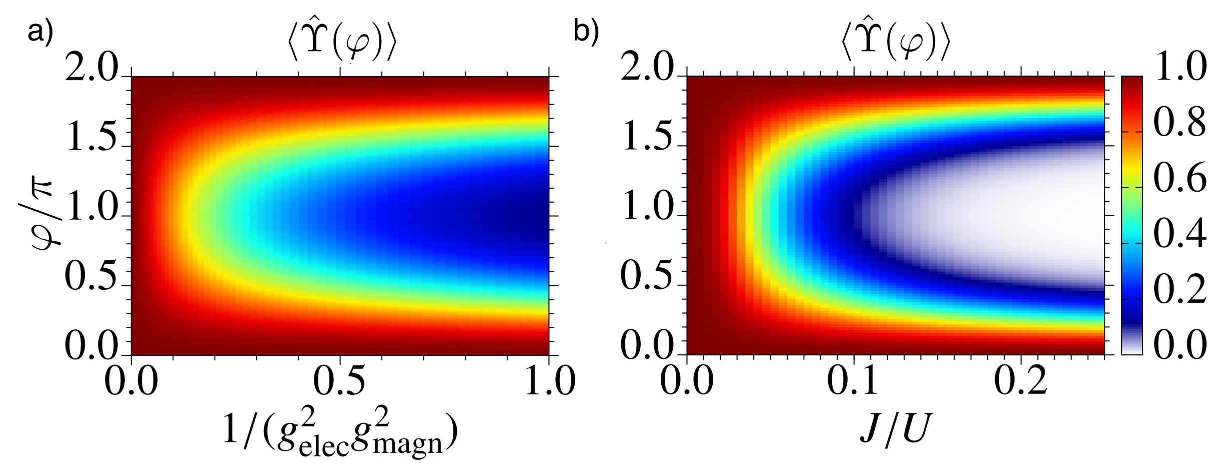


We show a protocol to measure string operators:





PRL 115, 240502 (2015) PHYSICAL REVIEW LETTERS week ending 11 DECEMBER 2015

University of the Basque Country

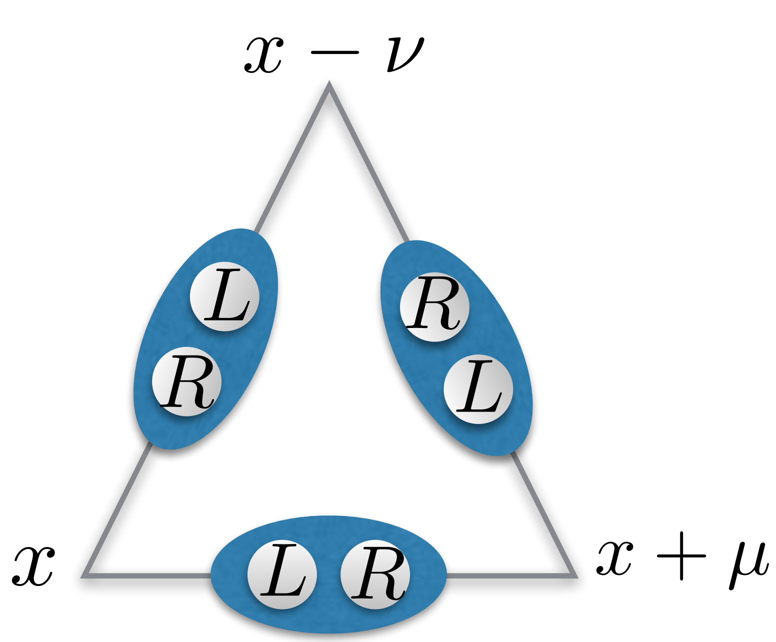
ikerbasque Basque Foundation for Science

Non-Abelian SU(2) Lattice Gauge Theories in Superconducting Circuits

A. Mezzacapo,[1,2] E. Rico,[1,3] C. Sabín,[4] I. L. Egusquiza,[5] L. Lamata,[1] and E. Solano[1,3]

Digital simulation of a non-abelian gauge field

$$H_T = -\mathrm{Tr}\left[U(\vec{x},\hat{\mu})U(\vec{x}+\hat{\mu},\hat{\nu})U(\vec{x}+\hat{\mu}+\hat{\nu},-\hat{\mu}-\hat{\nu})\right]$$



PRL 115, 240502 (2015) PHYSICAL REVIEW LETTERS week ending 11 DECEMBER 2015

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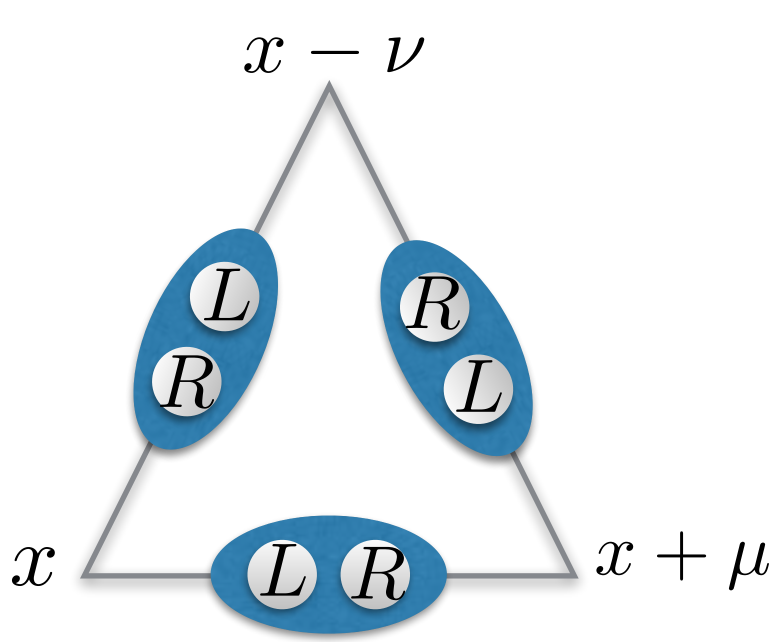
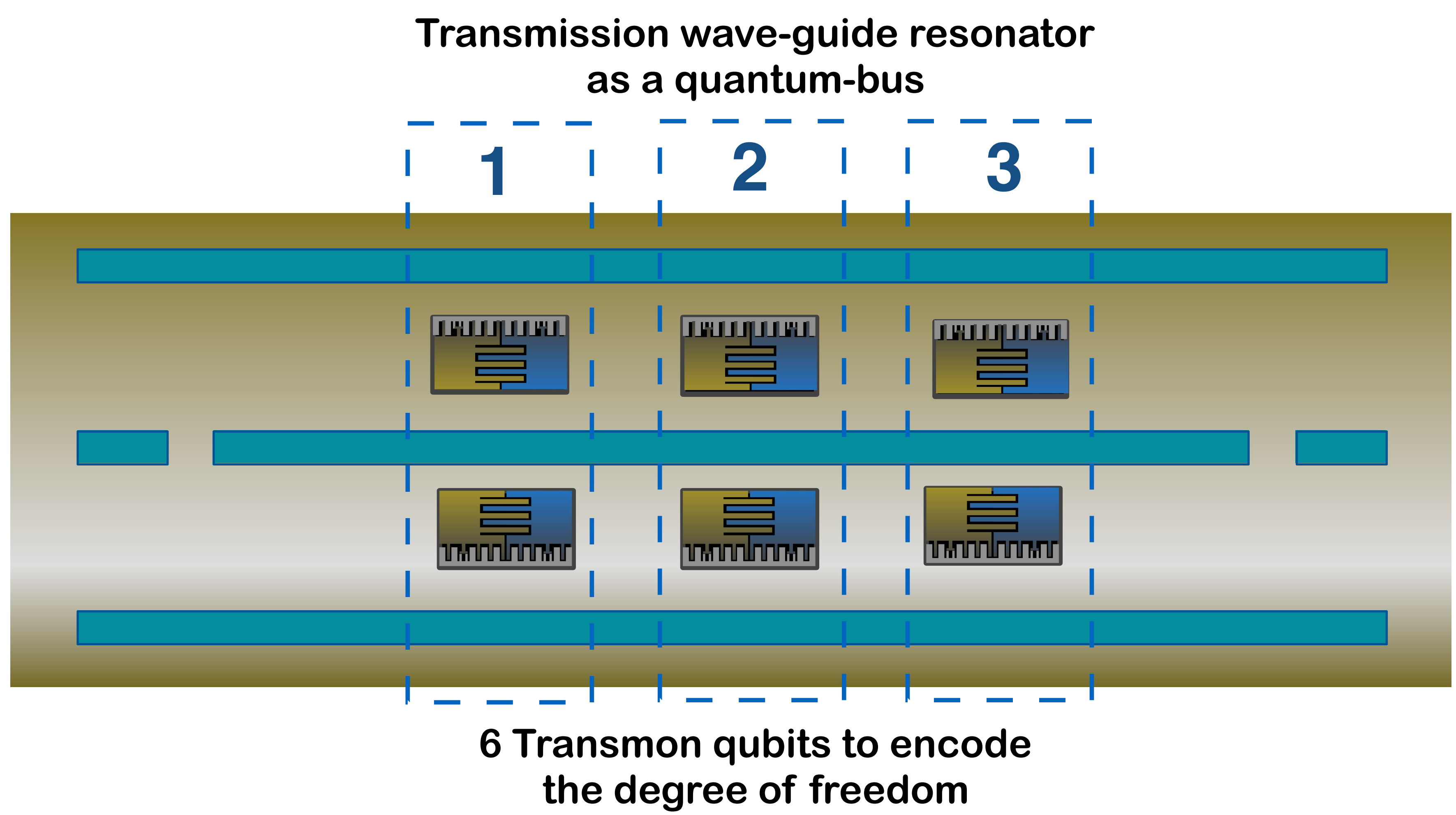
Digital simulation of a non-abelian gauge field

$$H_T = -\mathrm{Tr}\left[U(\vec{x},\hat{\mu})U(\vec{x}+\hat{\mu},\hat{\nu})U(\vec{x}+\hat{\mu}+\hat{\nu},-\hat{\mu}-\hat{\nu})\right]$$





The team

High-energy physics and lattice QCD:

D. Banerjee
M. Bögli
P. Stebler
P. Widmer
U.-J. Wiese

Bern

AMO and circuit-QED implementations:

G.K. Brennen, M. Dalmonte, I.L. Egusquiza, M. Hafezi, L. Lamata, D. Marcos, A. Mezzacapo, M. Müller, G. Pupillo, P. Rabl, C. Sabín, E. Solano, T.M. Stace, D. Vodola, P. Zoller

Bilbao, Innsbruck, Madrid, Maryland, New York, Nottingham, Queensland, Strasbourg, Sydney, Vienna

Classical simulations and tensor networks:

T. Calarco
S. Montangero
T. Pichler
P. Silvi
F. Tschirsich

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Related works: Lewenstein (Barcelona), Verstraete (Ghent-Vienna), Berges-Oberthaler (Heidelberg), Bañuls-Cirac-Jansen-Reznik (Munich-Tel Aviv-Zeuthen)

University of the Basque Country

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Basque Foundation for Science

Gauge fields, Holography, Topology

Home | Program | Registration | Participants

Invited speakers

- M. Aidelsburger (LMU, Munich)
- M.C. Bañuls (MPQ, Munich)
- A. Bermudez (Complutense Univ., Madrid)
- B.A. Bernevig (Princeton Univ.)
- H. Bombin (Yukawa ITP)
- M. Dalmonte (SISSA & ICTP, Trieste)
- A. Dauphin (ICFO, Barcelona)
- G. De las Cuevas (Innsbruck Univ.)
- J. Eisert (FU, Berlin)
- L. Fallani (LENS, Florence)
- P. Hauke (Heidelberg U.)
- S. Iblisdir (Barcelona Univ.)
- F. Jendrzejewski (Heidelberg U.)
- C. Kokail (IQOQI & Innsbruck Univ.)
- S. Kostka (NSC, Poland)
- M.A. Martín-Delgado (Complutense U., Madrid)
- K. Meichanetzidis (Oxford Univ.)
- A. Miyake (Univ. New Mexico)
- T. Neupert (Zurich Univ.)
- J. Pachos (Leeds Univ.)
- F. Pollmann (TUM, Munich)
- N. Regnault (ENS Paris)
- M. Ringbauer (Innsbruck Univ.)
- L. Santos (Hannover Univ.)
- S. Singh (Max-Planck Inst., Potsdam)
- T. Stace (Univ. Queensland, Brisbane)
- F. Verstraete (Ghent & Vienna Univ.)